Extreme Beams for Mysterious Particles

Regina Rameika
Fermilab
April 23, 2010

U.S. DEPARTMENT OF ENERGY

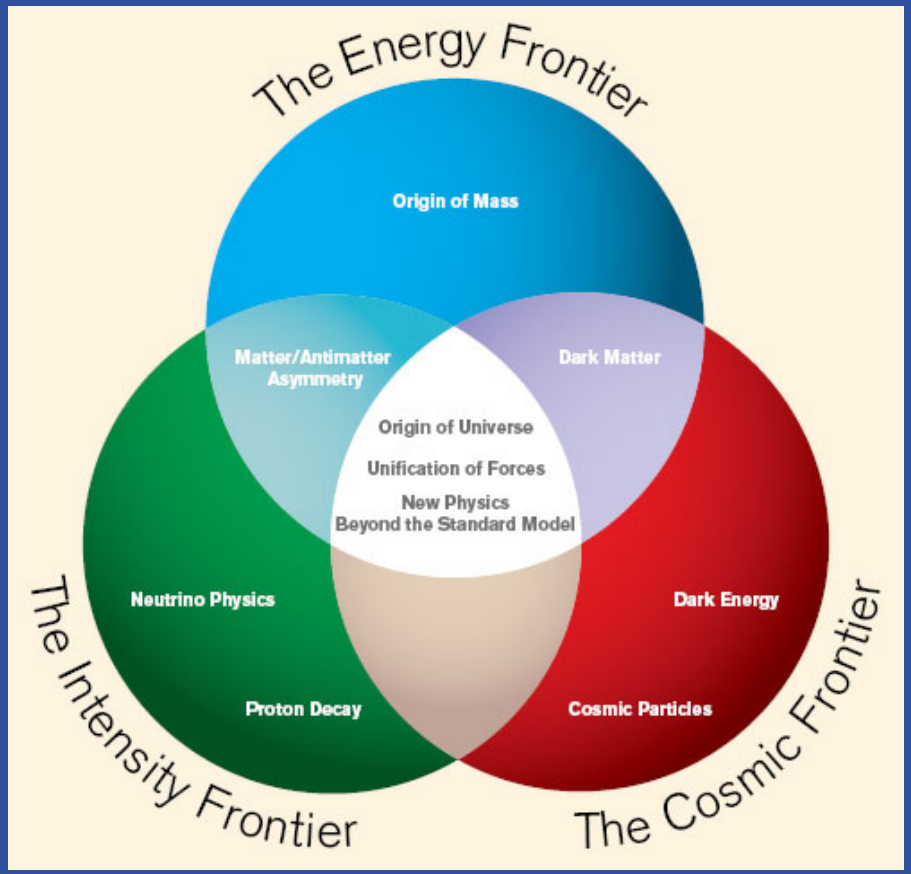
Fermilab

Extreme Beams are Fermilab's specialty

The questions we strive to answer

- What is the nature of the universe and what is it made of?
- What are matter, energy, space and time?
- How did we get here and where are we going?

Frontiers for Discovery Science

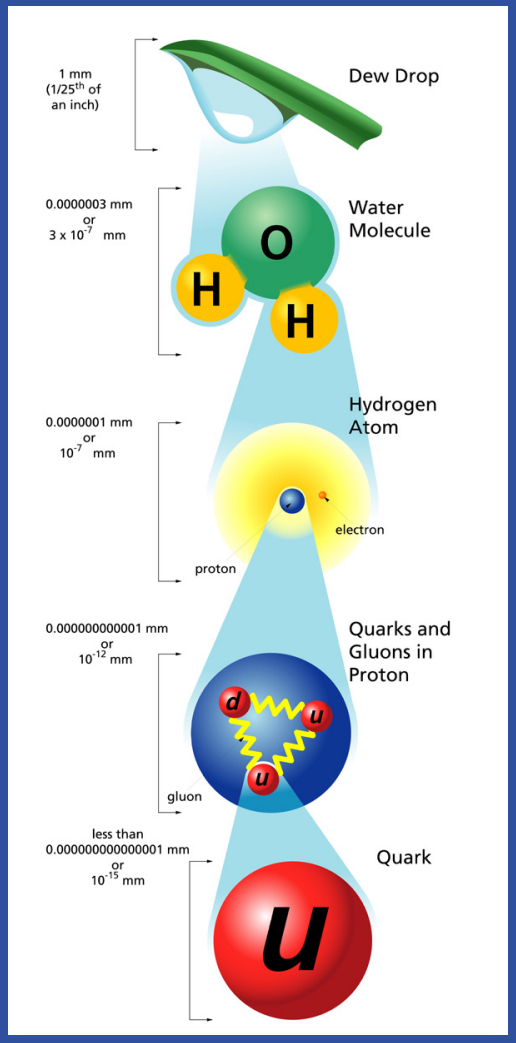


U.S. DEPARTMENT OF ENERGY

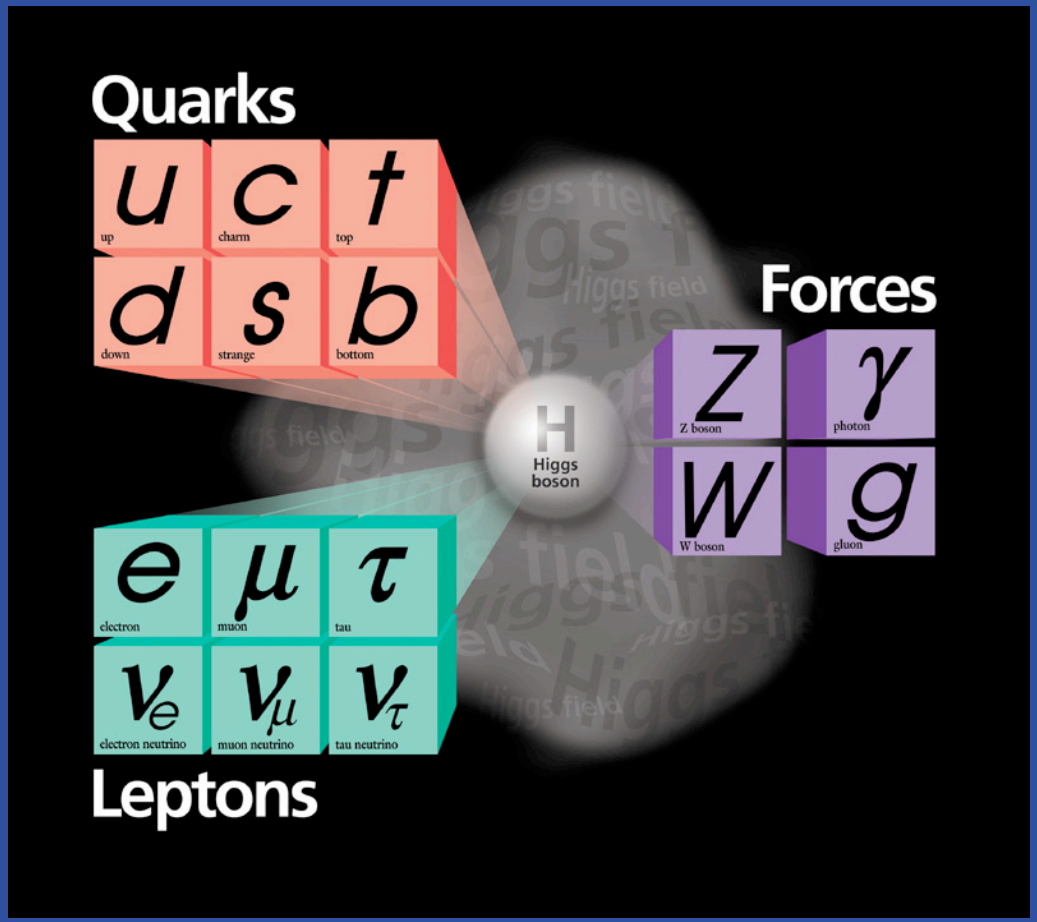
OFFICE OF HIGH ENERGY PHYSICS

Office of Science HEP

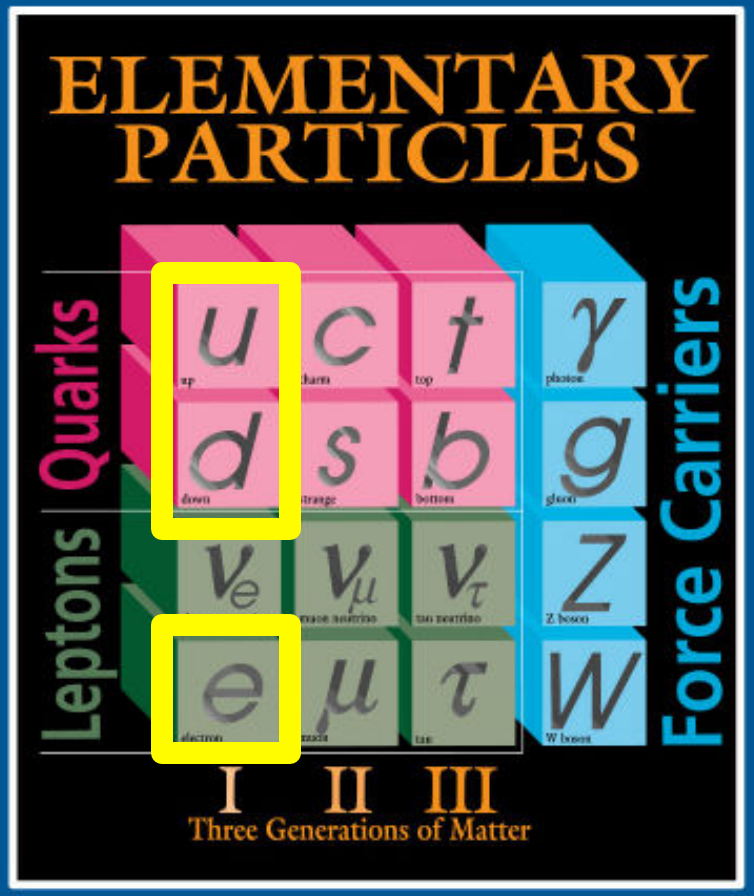
Searching for the fundamental building blocks

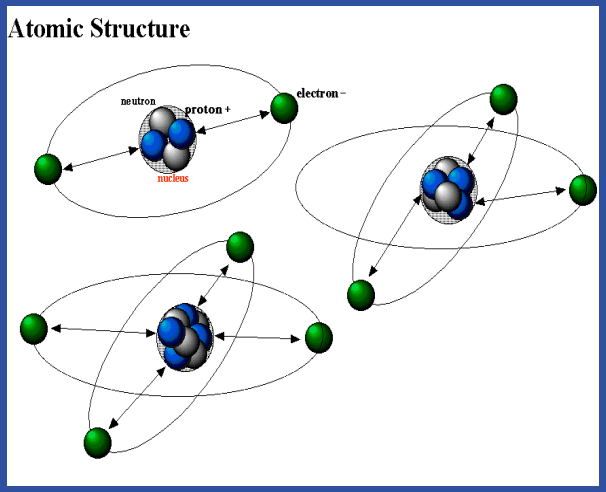


The Standard Model

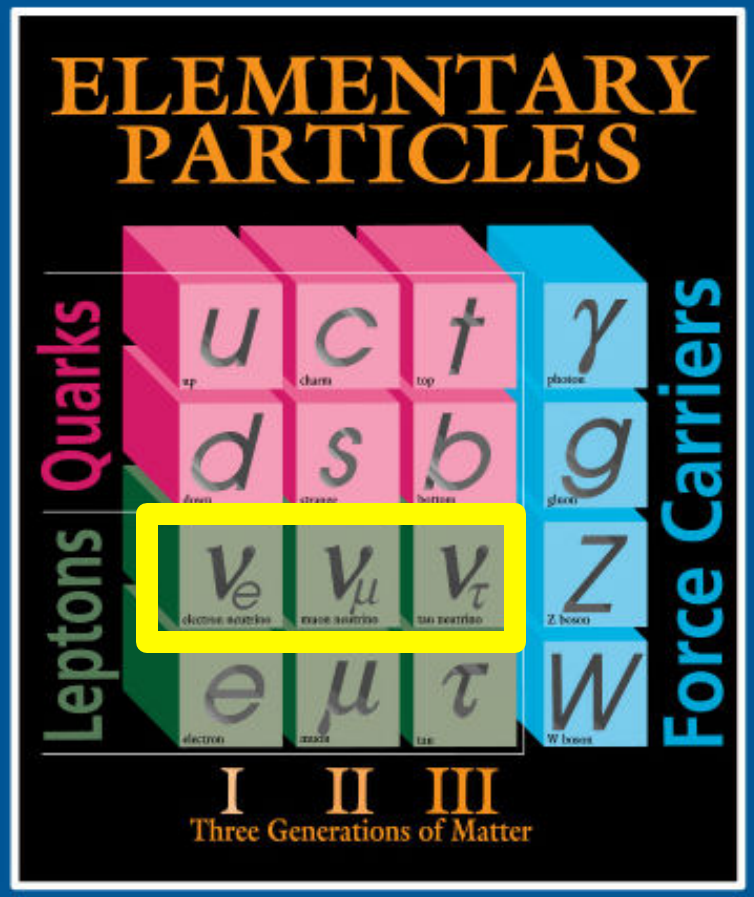


Our Everyday World





Tonight's Lecture



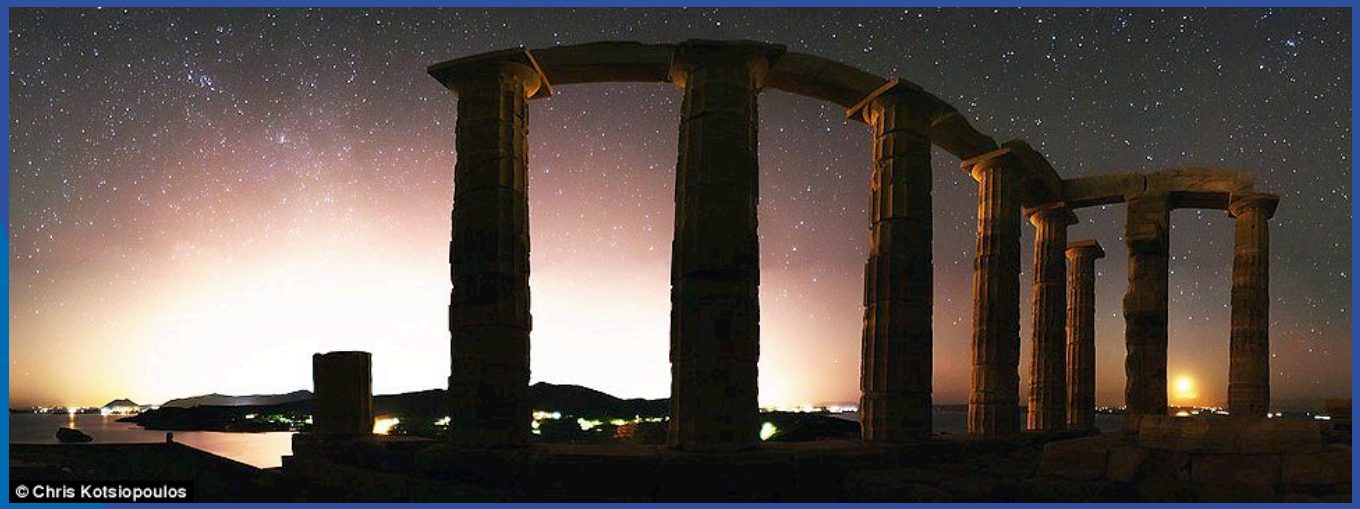
How *and why* we use our powerful proton accelerator to create intense beams of one of nature's most elusive and mysterious particles : the neutrino

What is a neutrino?

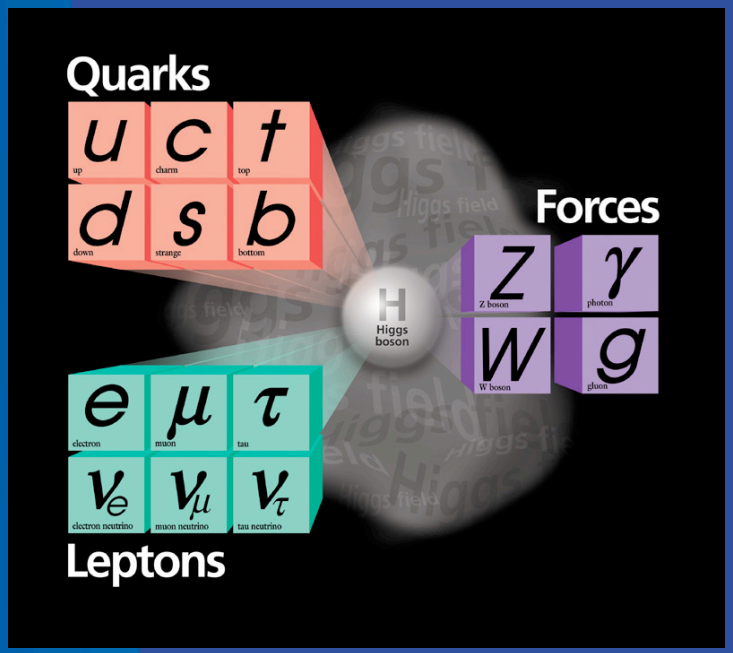
- The neutrino is an elementary particle which holds no electric charge, travels at nearly the speed of light, and passes through ordinary matter with virtually no interaction.
- The existence of the neutrino was postulated in 1930 as an explanation for the apparent non-conservation of energy in the process of radioactive decays
- Throughout the 20th century the neutrino played an important role in the evolving understanding of elementary particles and the forces with which they interact

The Matter of the Universe

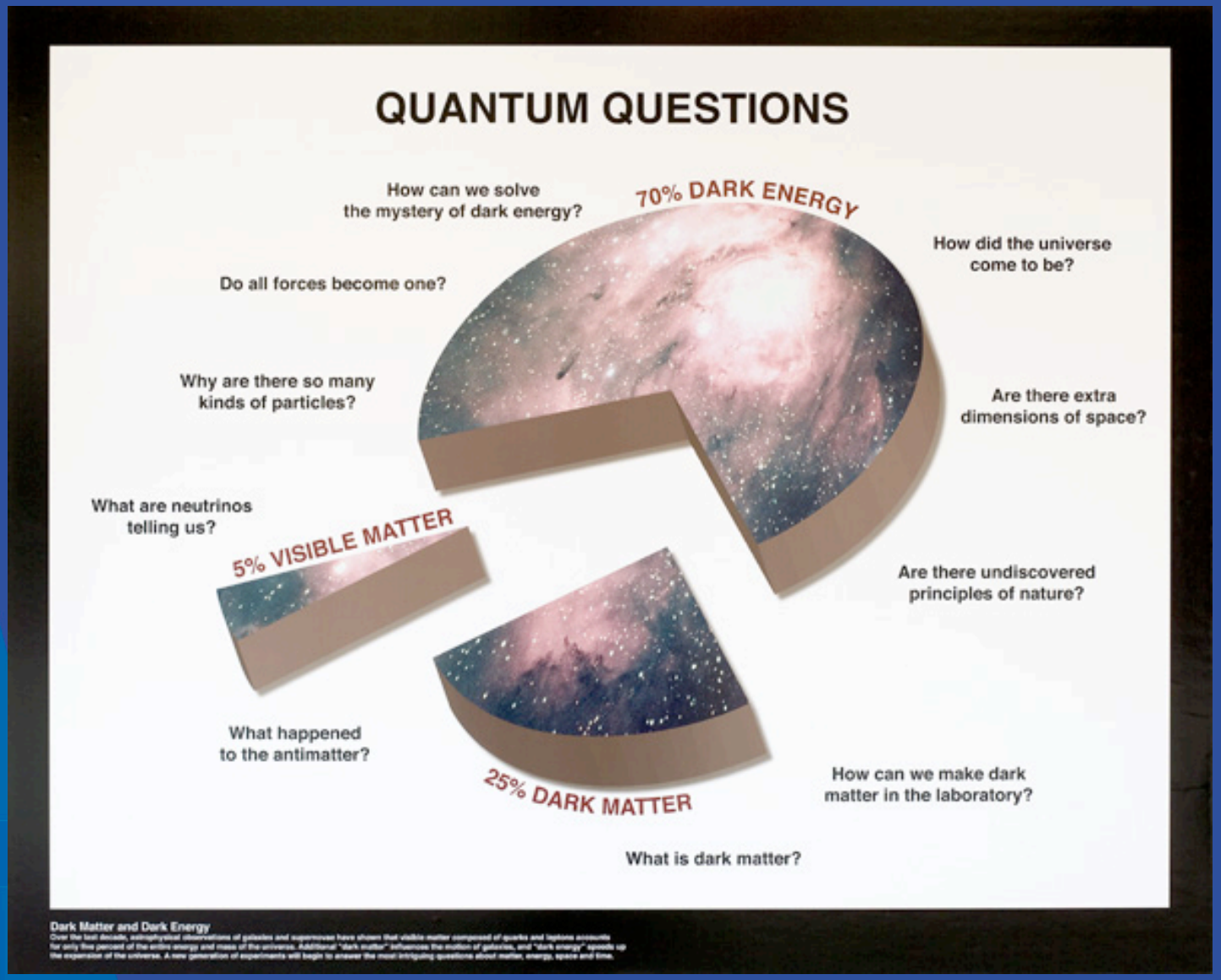
- Our observations of the cosmos suggests there is more to the story than our simple model of building blocks :
  - The universe is made of matter; why aren't there anti-stars and anti-galaxies?
  - Neutrinos have mass. They contribute at least as much mass in the universe as the stars and their planets.
  - Most of the mass of the universe is new types of particles yet to be discovered at accelerators.



Connecting Quarks with the Cosmos

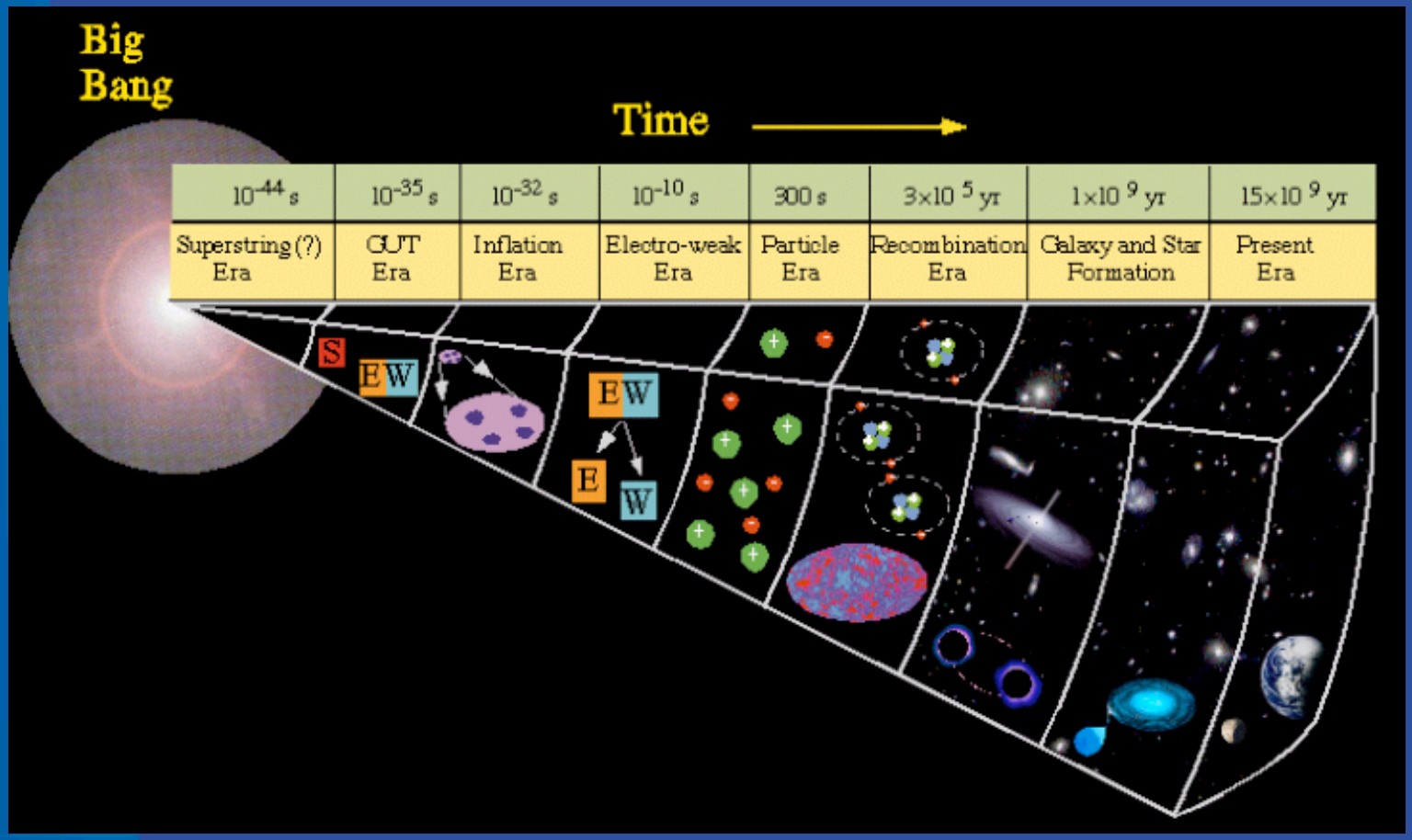


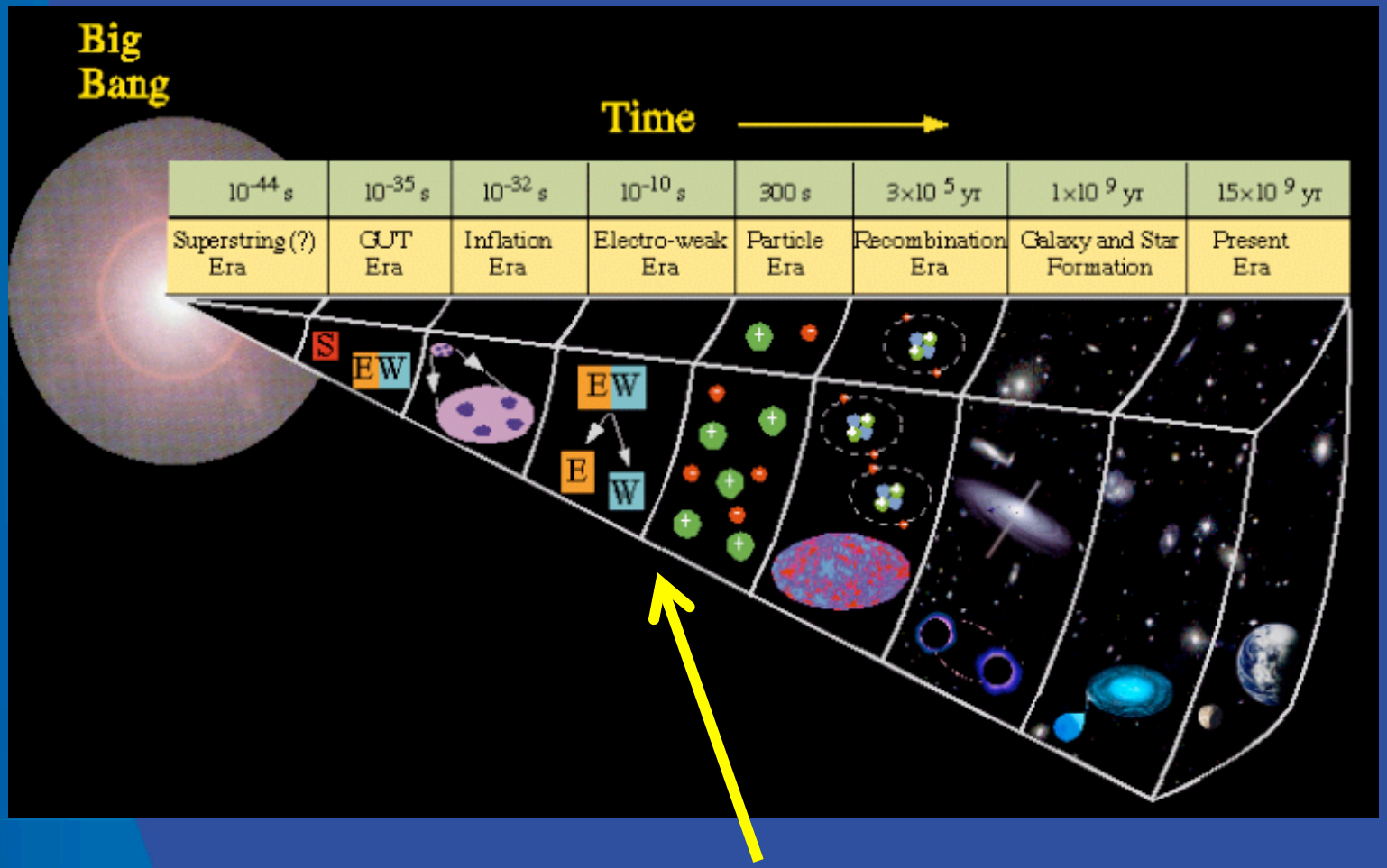
THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine


QUANTUM QUESTIONS
How can we solve the mystery of dark energy?
70% DARK ENERGY
How did the universe come to be?
Do all forces become one?
Why are there so many kinds of particles?
Are there extra dimensions of space?
What are neutrinos telling us?
5% VISIBLE MATTER
Are there undiscovered principles of nature?
What happened to the antimatter?
25% DARK MATTER
How can we make dark matter in the laboratory?
What is dark matter?
Dark Matter and Dark Energy

How did our universe come to be the way it is (or how we think it is)?

Big Bang Theory

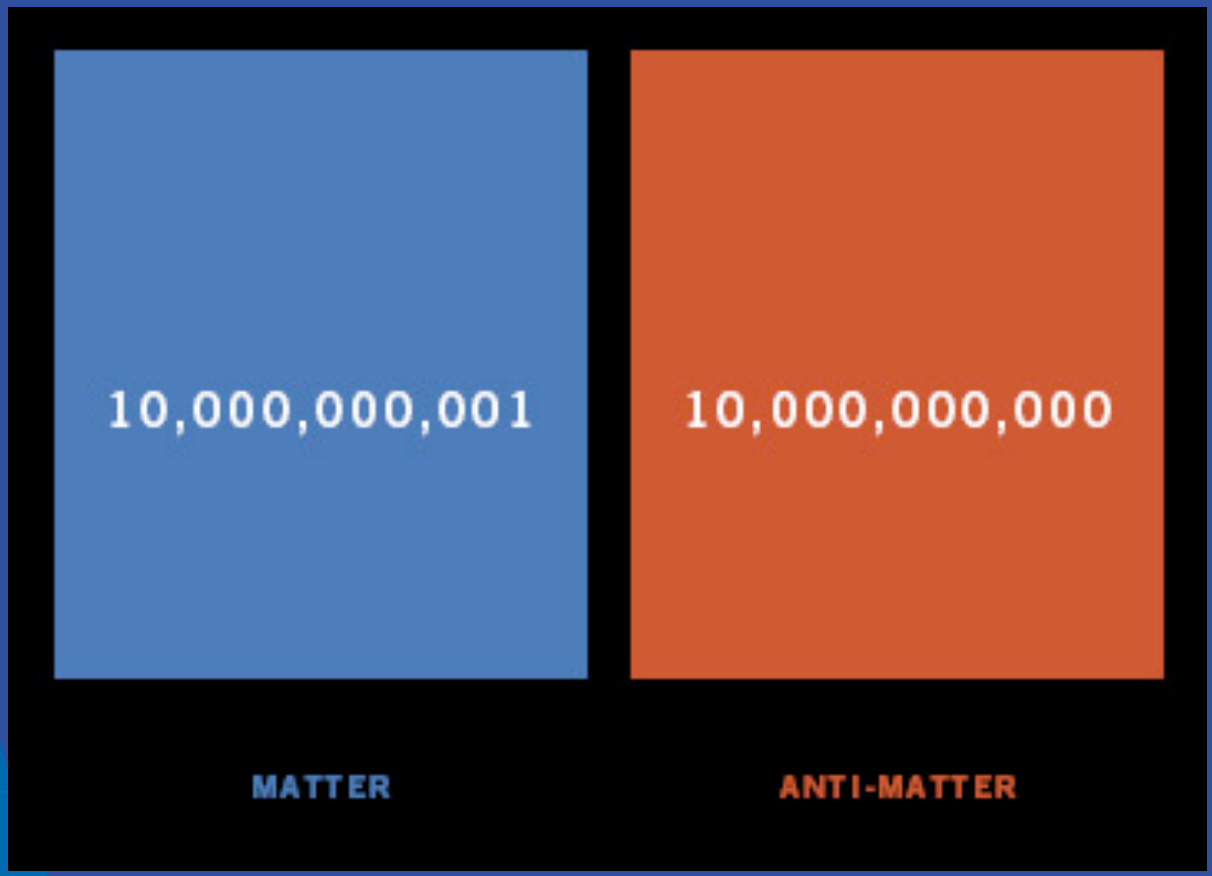

Big Bang
Time
10^{-44} s
10^{-35} s
10^{-32} s
10^{-10} s
300 s
3×10^{5} yr
1×10^{9} yr
15×10^{9} yr
Superstring (?) Era
GUT Era
Inflation Era
Electro-weak Era
Particle Era
Recombination Era
Galaxy and Star Formation
Present Era
S
EW
EW
E
W



Neutrinos created about 1 second after the Big Bang

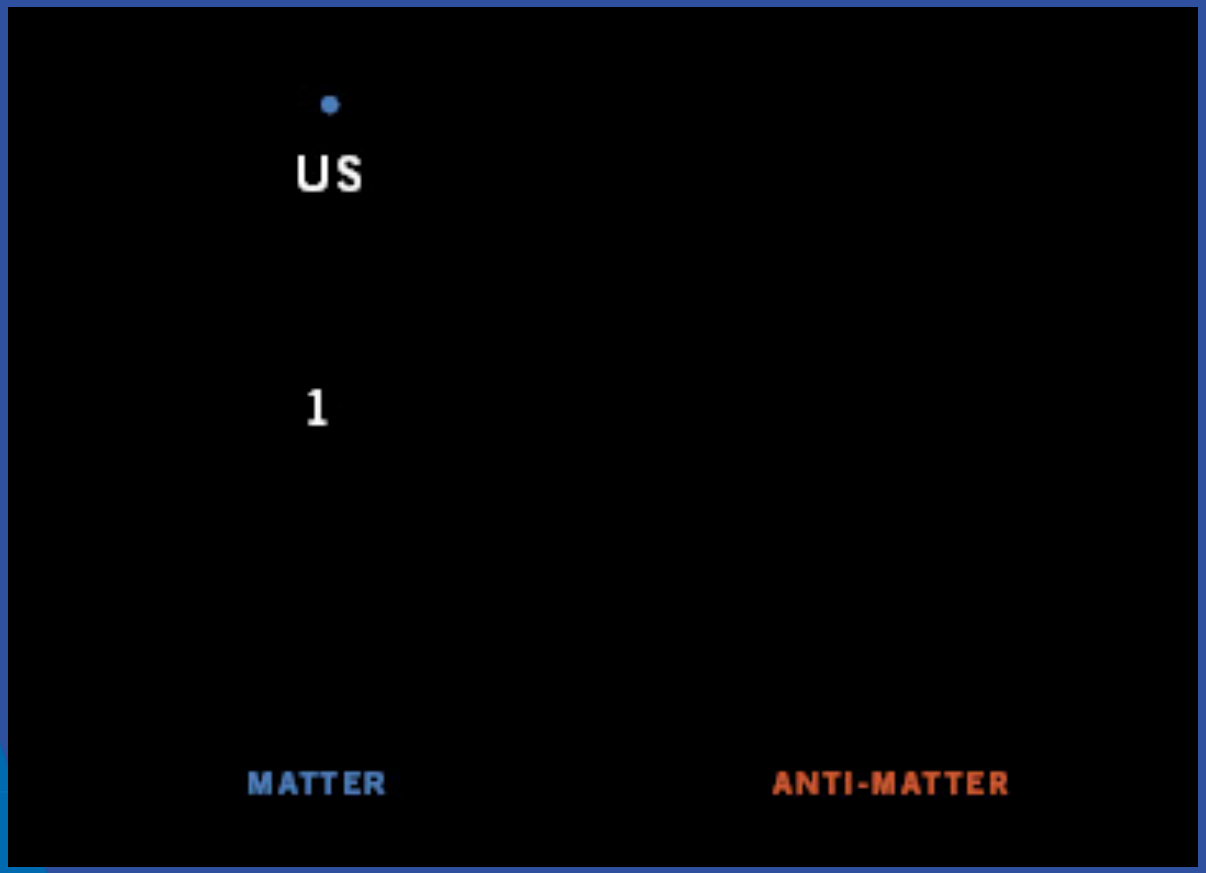
remain all around us today : 150 per cubic centimeter

A small imbalance of matter – antimatter



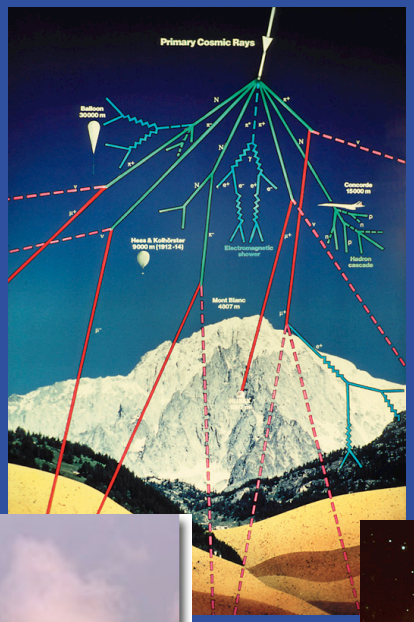
Credit : Hitoshi Murayama

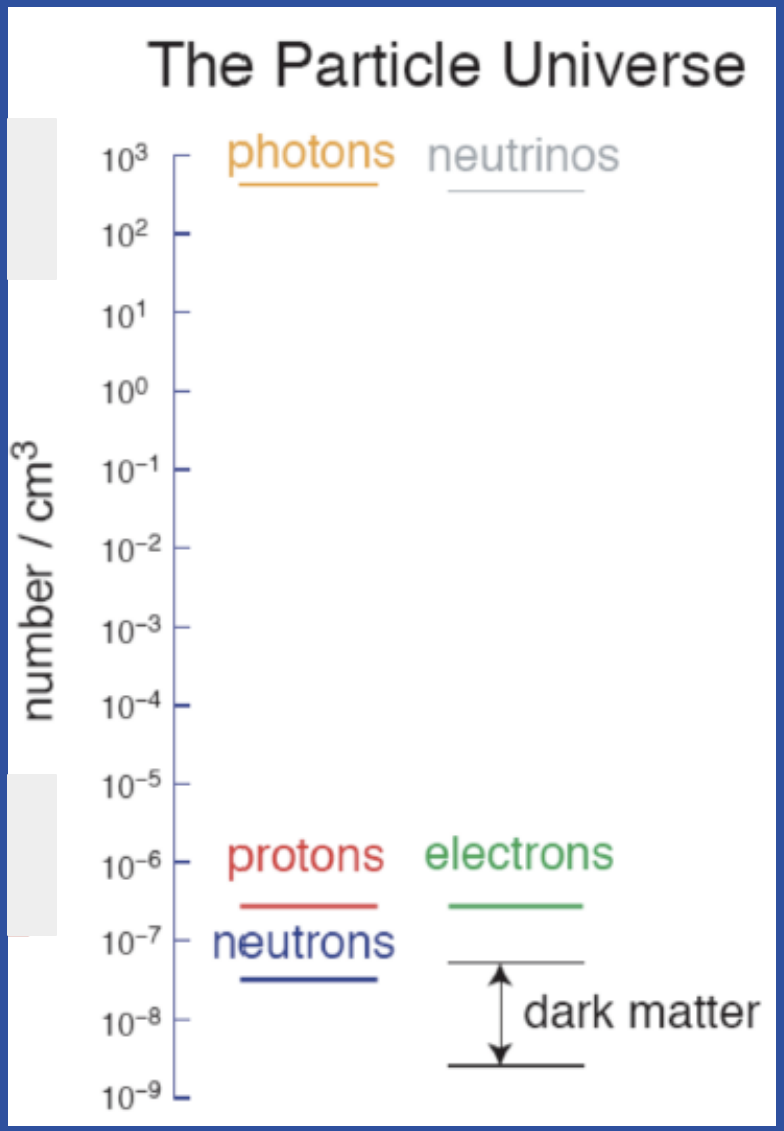
--- our matter world



What do neutrinos have to do with this asymmetry?

Neutrinos are abundant in our world




The Particle Universe
photons
neutrinos
protons
electrons
neutrons
dark matter
number / cm3
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9

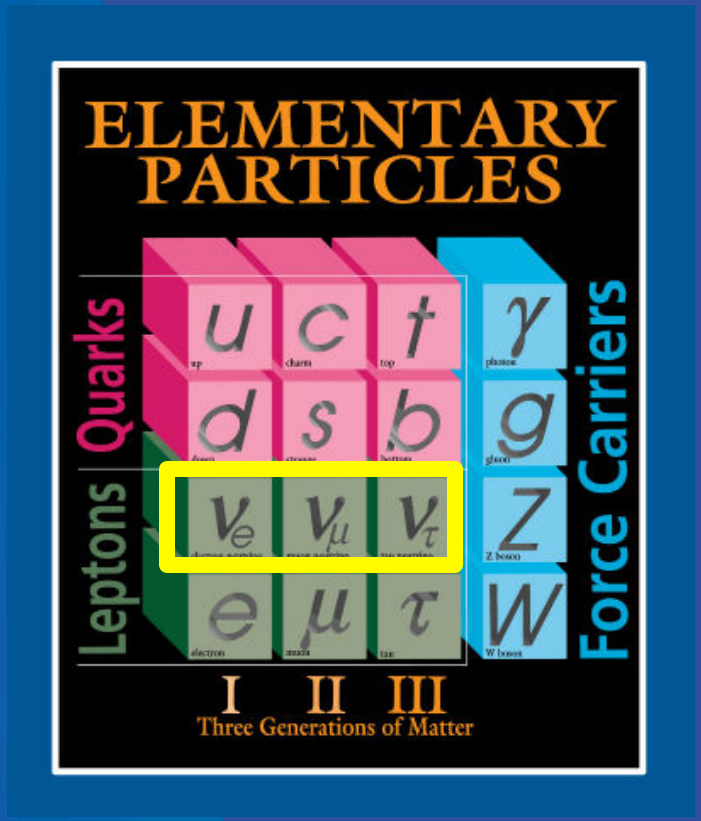
What do we know about these abundant particles?

Cosmic Gall

NEUTRINOS, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And scorning barriers of class,
Infiltrate you and me! Like tall
and painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
and pierce the lover and his lass
From underneath the bed-you call
It wonderful; I call it crass.

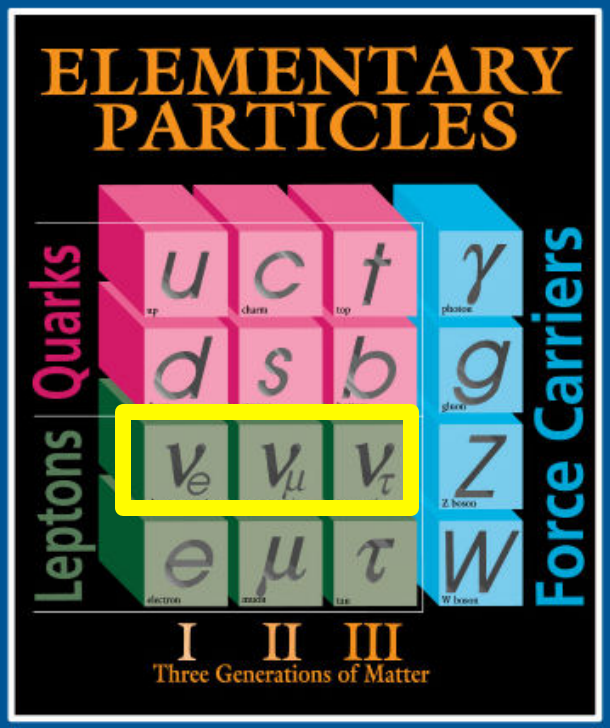
- *Telephone Poles and Other Poems*, John Updike, Knopf, 1960

We know …



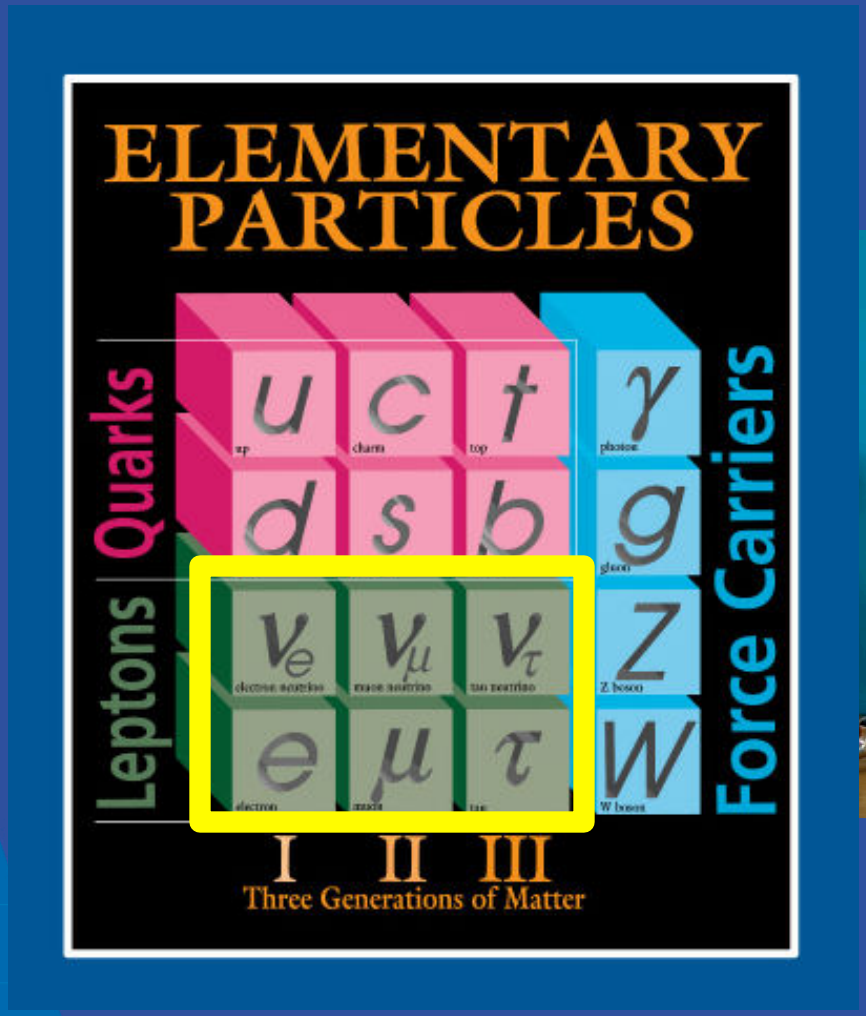
- There are three neutrino "flavors"
- Neutrinos are the 2nd most abundant particle in the universe
- Neutrinos do not interact very often
- Neutrinos have very small masses

We don't know …



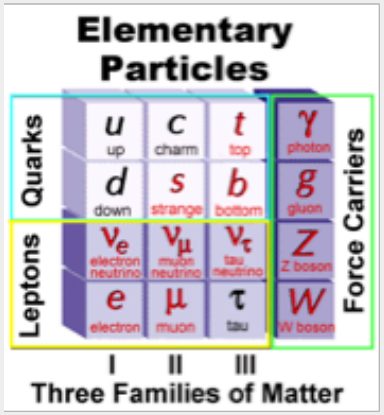
- What are the neutrino masses?
- How exactly are the neutrino masses and flavors related?
- What role did neutrinos play in the evolution of our matter universe?
- Could neutrinos hold the answer to why we exist?

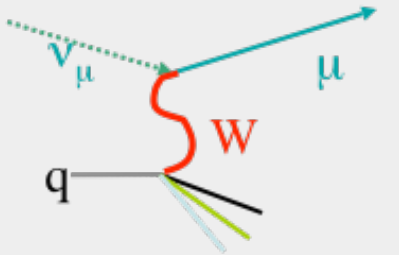
If we want to study neutrinos, how do we create and detect them?


ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u
c
t
γ
d
s
b
g
ν_e
ν_μ
ν_τ
Z
e
μ
τ
W
I II III
Three Generations of Matter


ν_e
ν_μ
ν_τ

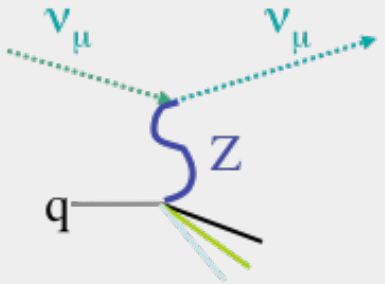
Neutrino Flavors & Interactions





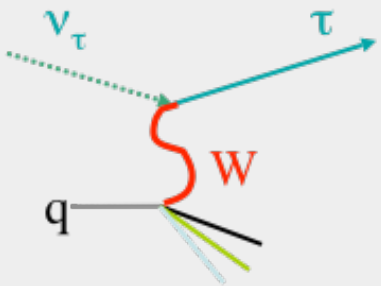
$\nu_\mu + N \rightarrow \mu^- + X$

Charged current



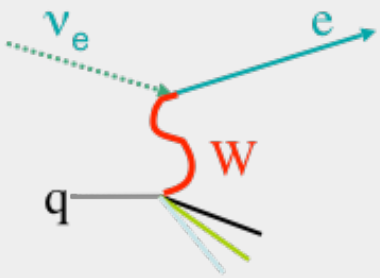
$\nu_\mu + N \rightarrow \nu_\mu + X$

Neutral current



$\nu_\tau + N \rightarrow \tau^- + X$

Tau Charged current



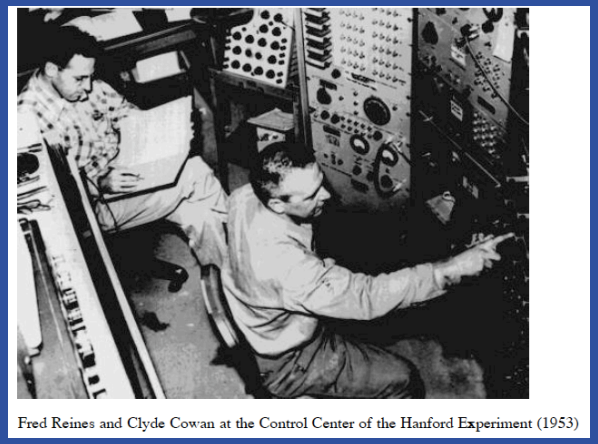
$\nu_e + N \rightarrow e^- + X$

Electron Charged current

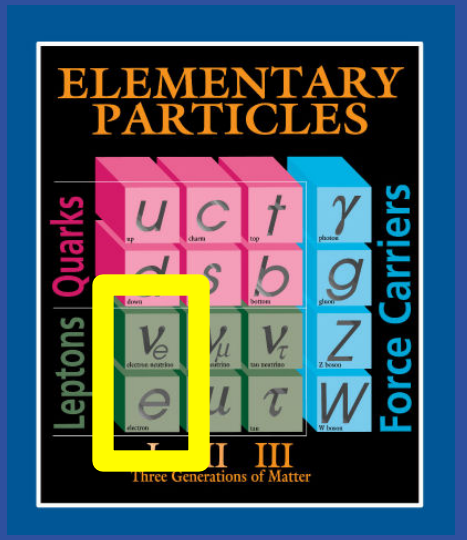
Experimental neutrino history in 5 minutes

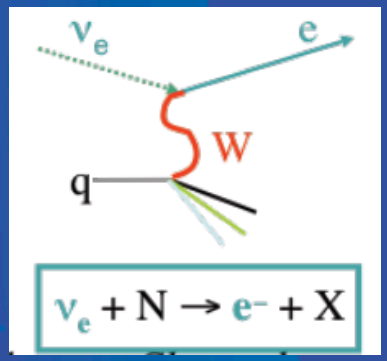
1st detection of neutrinos -1950s

Savannah River Nuclear Reactor

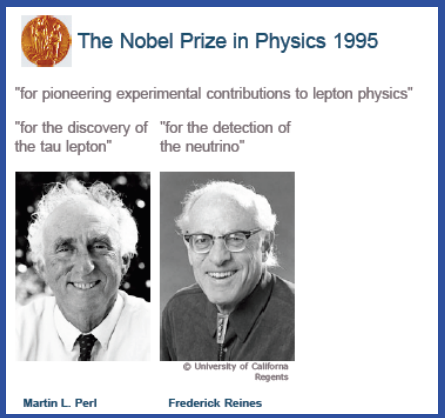


Fred Reines and Clyde Cowan at the Control Center of the Hanford Experiment (1953)

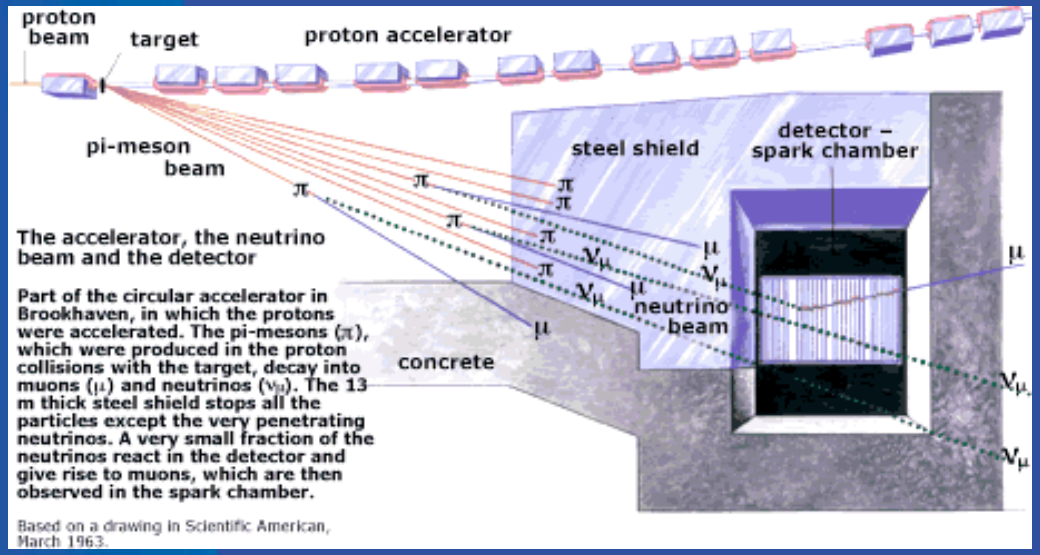


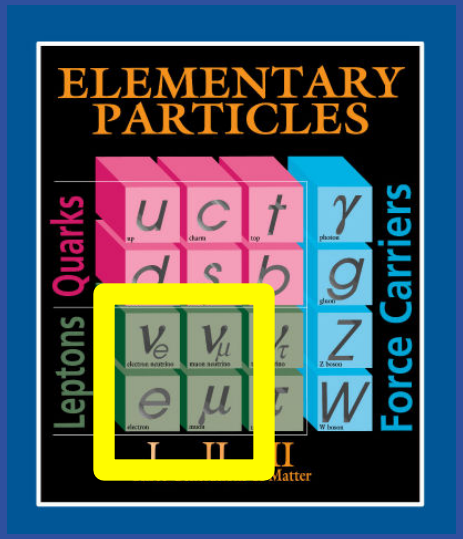


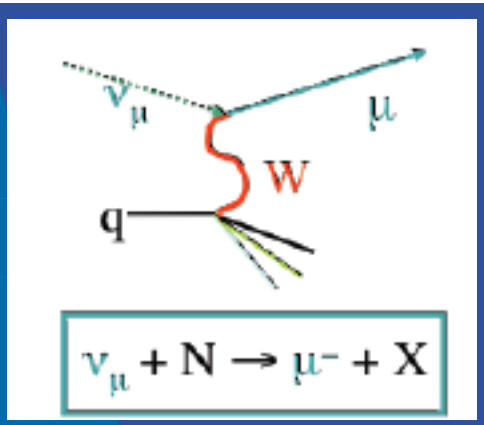
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

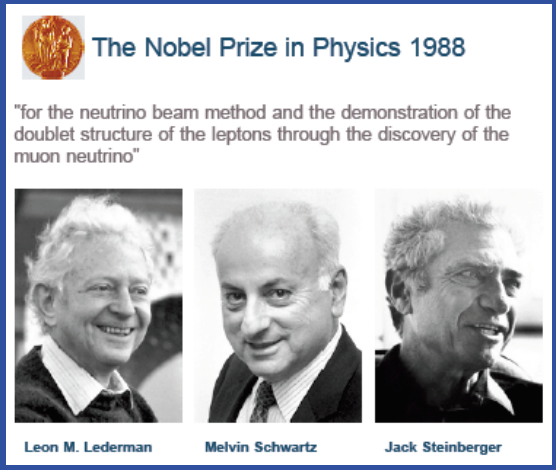


Discovery of “two neutrinos” – 1960s

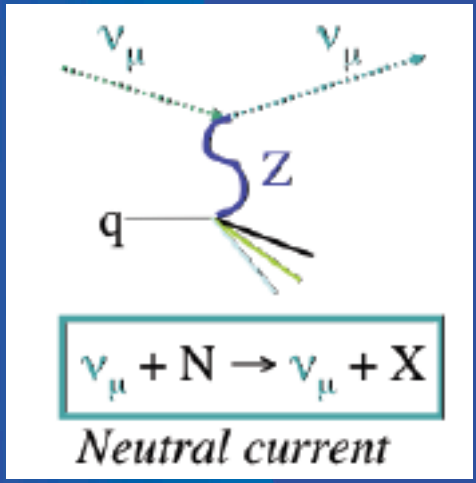


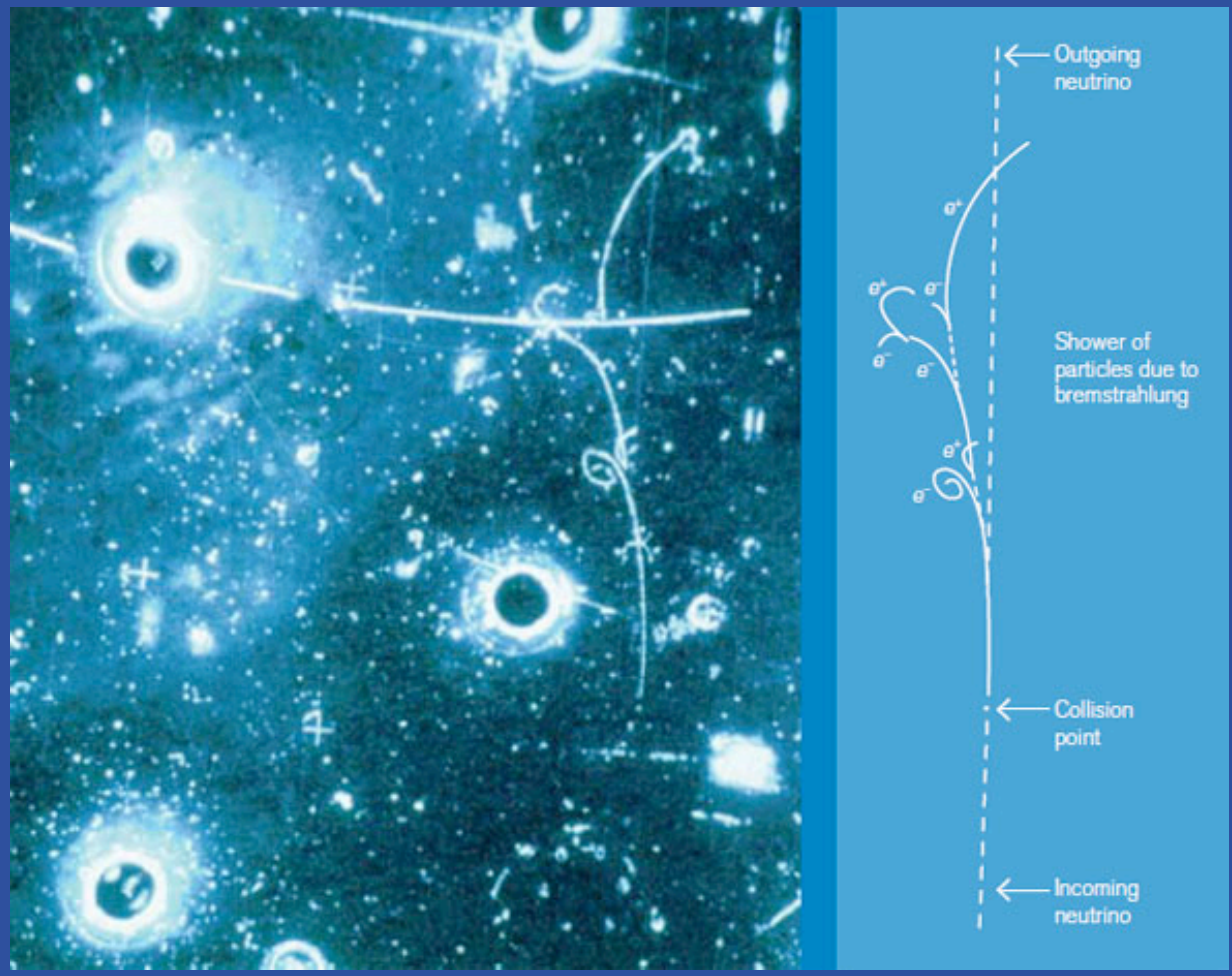






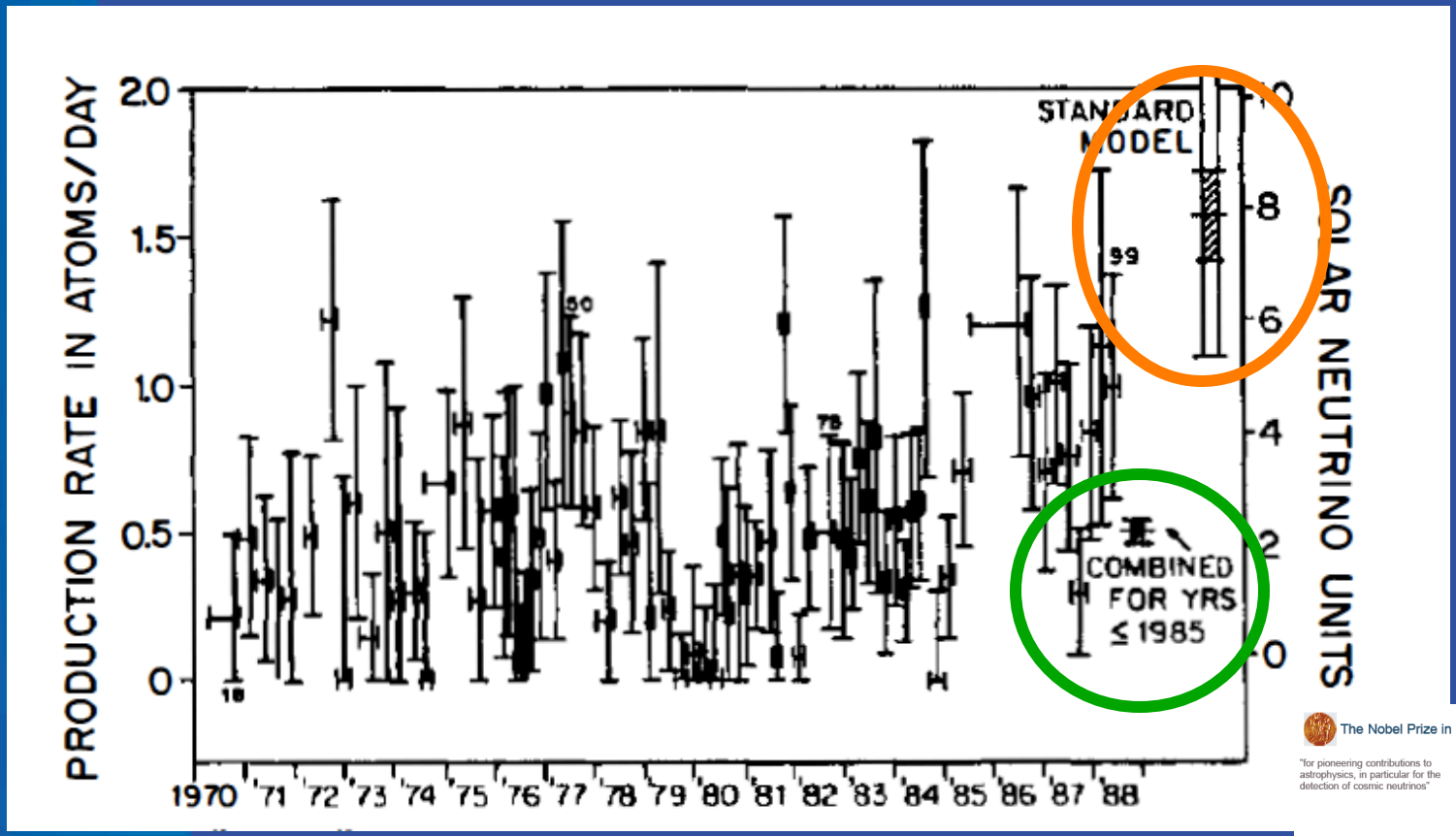
Discovery of neutral currents – 1974





Detecting neutrinos from our sun - 1970's

$$\nu_e + {}^{37}\mathrm{Cl} \mapsto {}^{37}\mathrm{Ar} + e^-$$


PRODUCTION RATE IN ATOMS/DAY
SOLAR NEUTRINO UNITS
2.0
1.5
1.0
0.5
0
10
8
6
4
2
0
STANDARD MODEL
COMBINED FOR YRS ≤ 1985
1970 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88


The Nobel Prize in Physics 2002
"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"
"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"
Raymond Davis Jr.
1/4 of the prize
USA
University of Pennsylvania
Philadelphia, PA, USA
b. 1914
d. 2006
Masatoshi Koshiba
1/4 of the prize
Japan
University of Tokyo
Tokyo, Japan
b. 1926
Riccardo Giacconi
1/2 of the prize
USA
Associated Universities Inc.
Washington, DC, USA
b. 1931
(in Genoa, Italy)

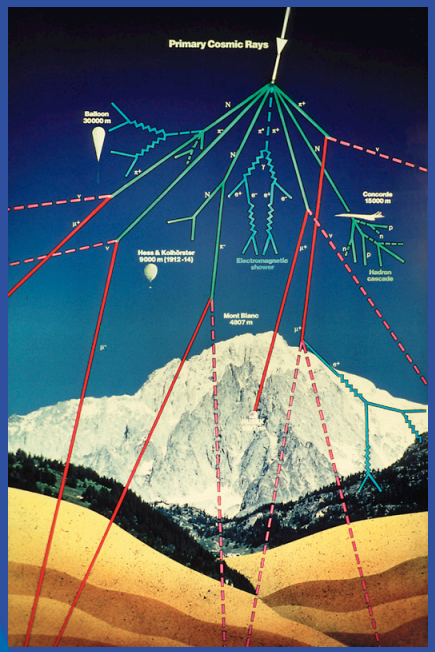
A very brief digression….

- Does the nucleon (proton, neutron) decay?

New detectors underground – 1980s

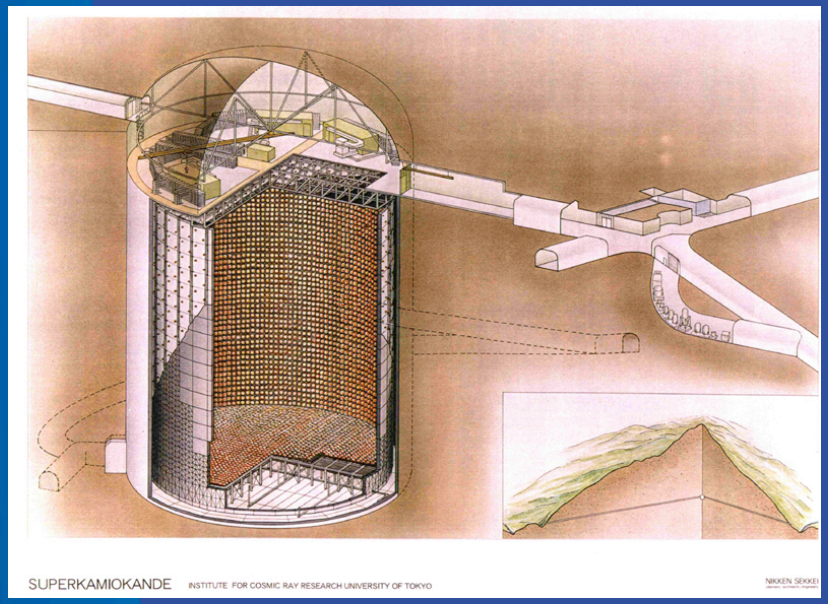
$$p \rightarrow e^{+} + \pi^{0}; \pi^{0} \rightarrow \gamma\gamma$$

No proton decay but new mysteries……
Neutrinos from cosmic ray interactions are easily detected in these deep underground detectors

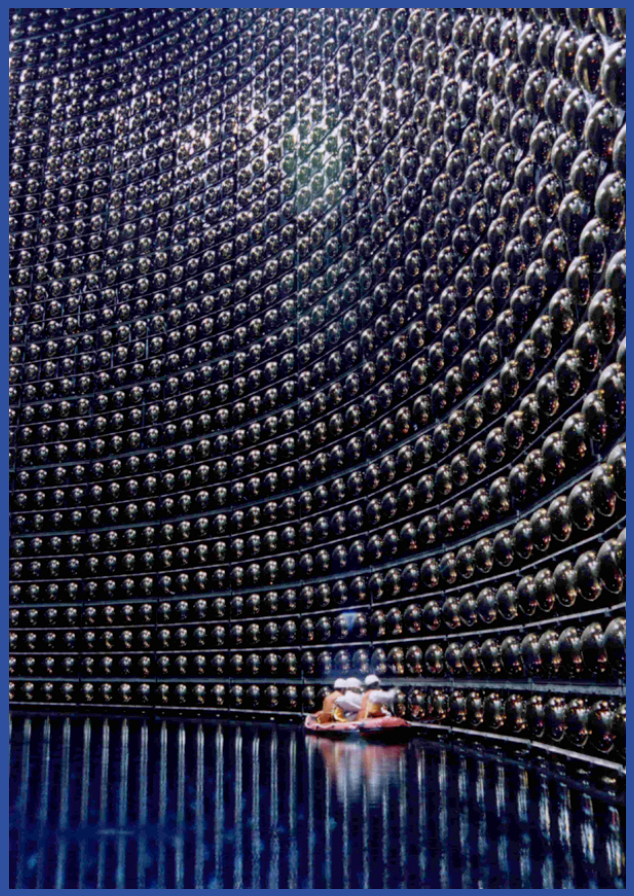


Half of the predicted muon neutrinos are “missing” !

A new era for neutrino physics – 1990s

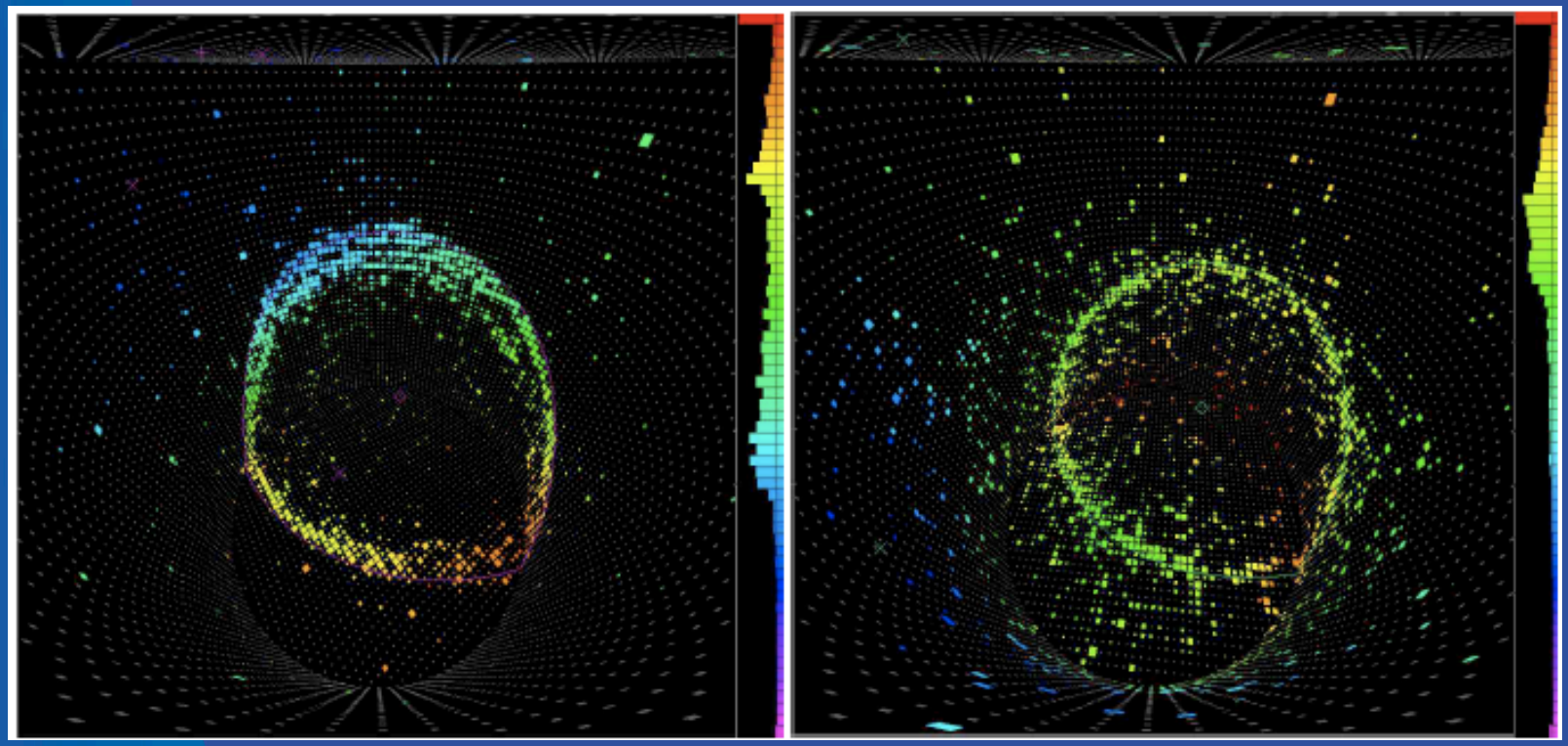


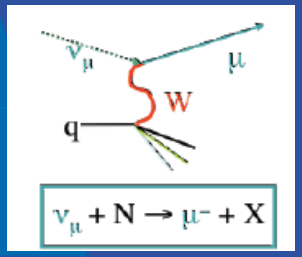
50,000 ton Water detector in the Kamioka Mine in Japan

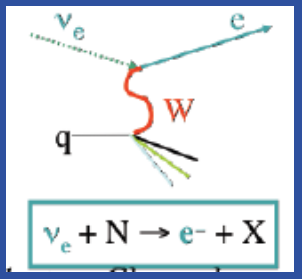


14,000 photo detectors

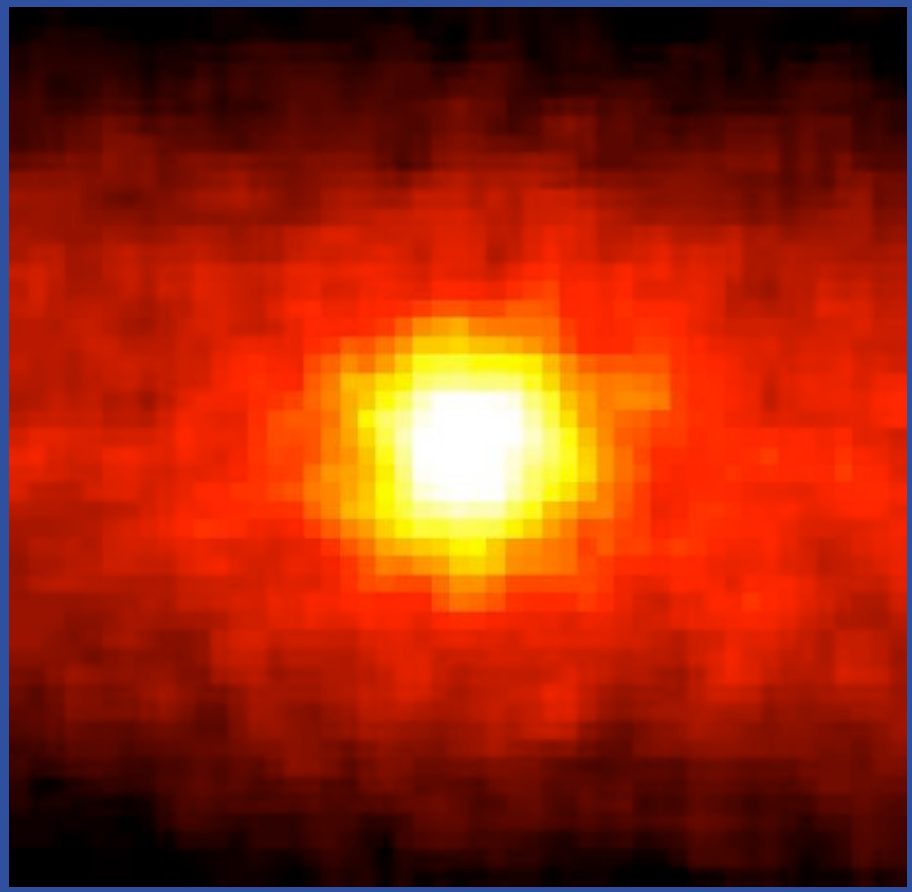
A camera for neutrinos



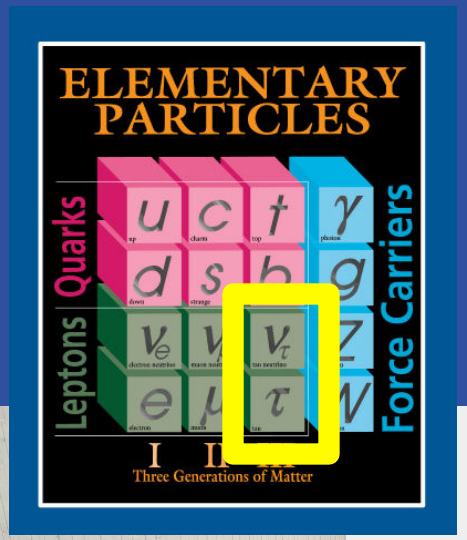


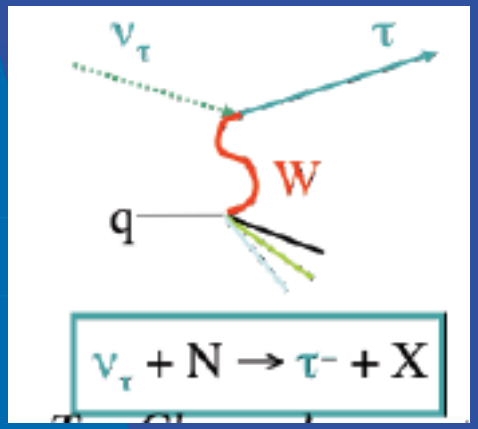


A neutrino image of the sun



IN 2000
A GROUP OF
PHYSICISTS FINALLY
FOUND EVIDENCE OF
THE TAU TYPE OF
THIS SUBATOMIC
PARTICLE

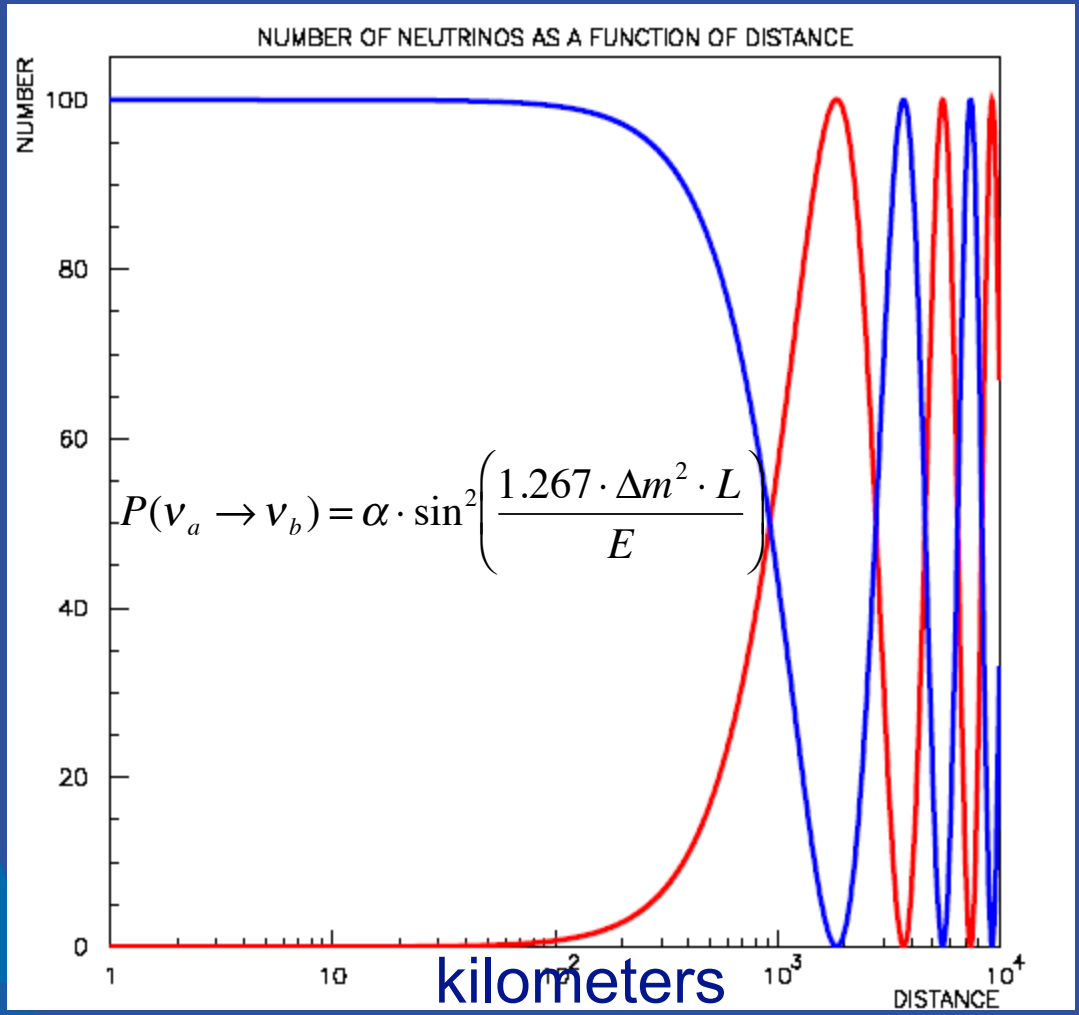




Smoking guns ……

- Solar neutrino rate is too low…..
- Atmospheric neutrino rate is too low….
- What makes up the “dark matter” of the universe?

Mystery of the missing neutrinos solved : Neutrino Oscillations !



$$P(\nu_a \rightarrow \nu_b) = \alpha \cdot \sin^2\left(\frac{1.267 \cdot \Delta m^2 \cdot L}{E}\right)$$

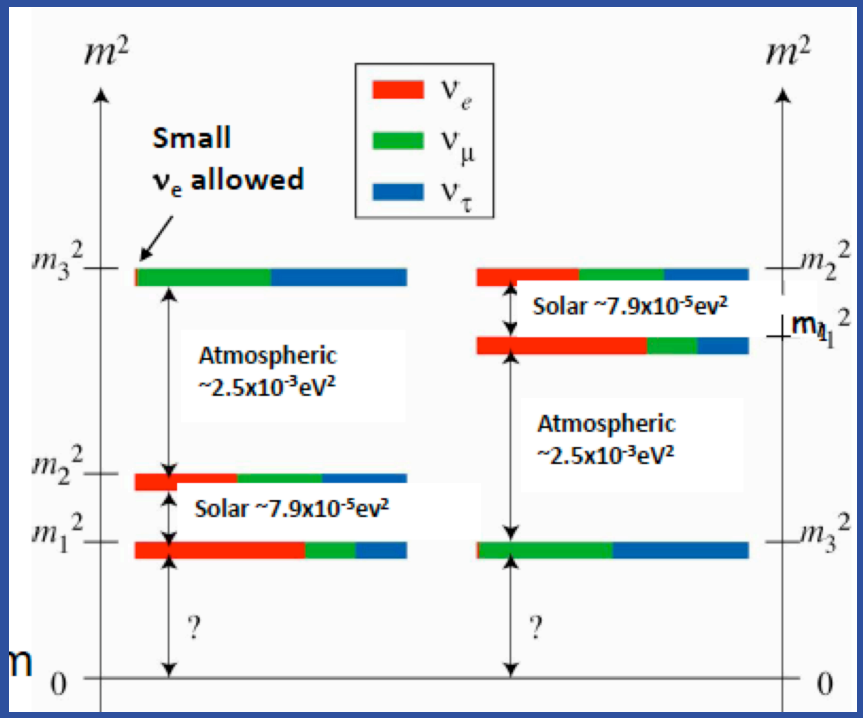
1998 – Discovery of neutrino oscillations ➔ neutrinos have mass!

A neutrino's mass will govern how it propagates through space;

It's flavor governs how it interacts (and gets detected)

Neutrino Mass and Flavors

???

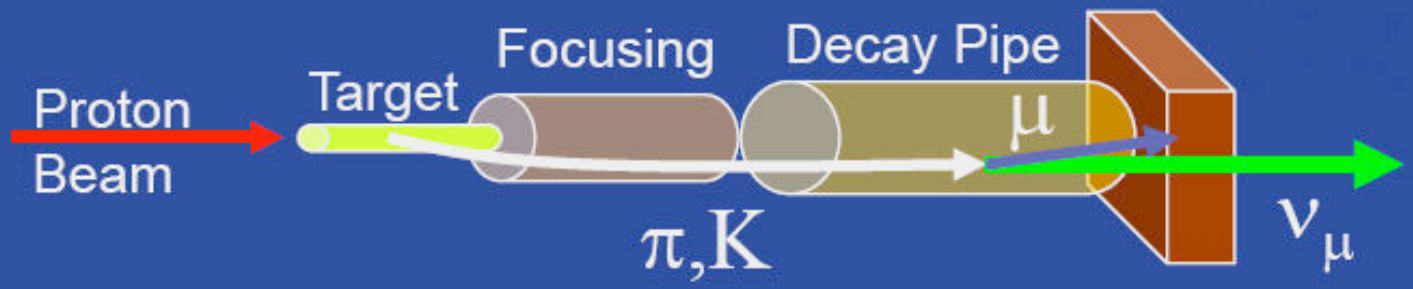


$$P(\nu_a \rightarrow \nu_b) = \alpha \cdot \sin^2\left(\frac{1.267 \cdot \Delta m^2 \, L}{E}\right)$$

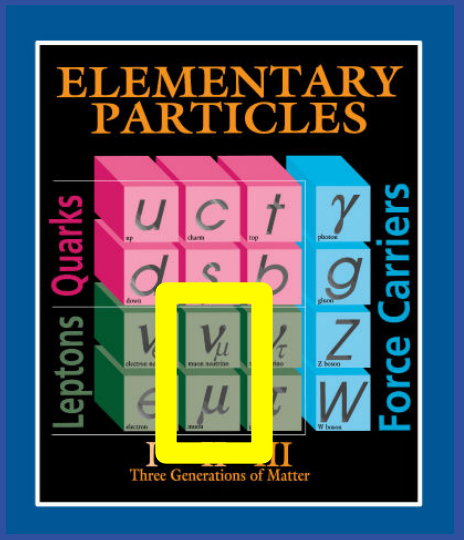
end of history lesson……..

On to a new era for accelerator neutrino experiments.

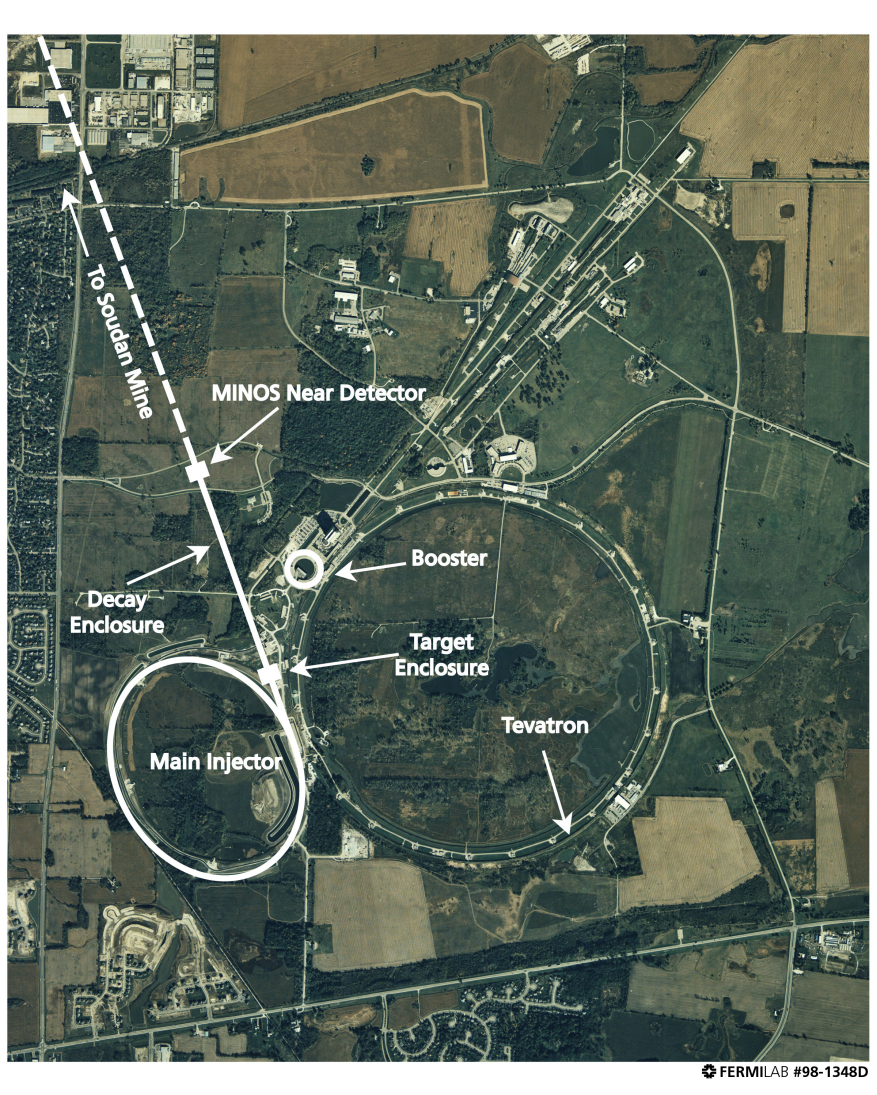
Making neutrinos at an accelerator



- High energy protons hit a target
- Unstable pion and kaon charged particles are produced
- The pions and kaons are “focused” by a magnetic field to go in the desired direction
- The pions and kaons decay into muons and muon type neutrinos
- The direction of the magnetic field determines whether neutrinos or anti-neutrinos are generated



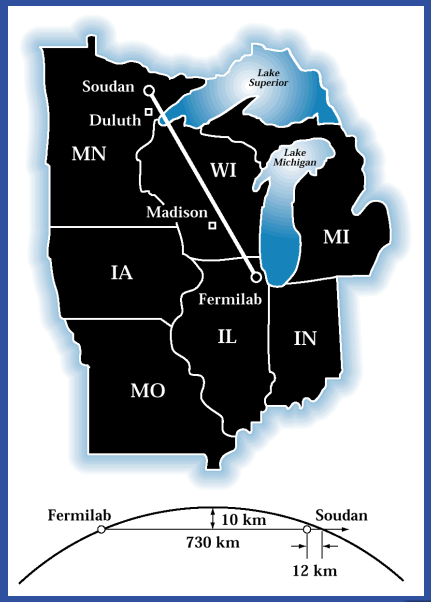
Neutrinos from the Main Injector - NuMI

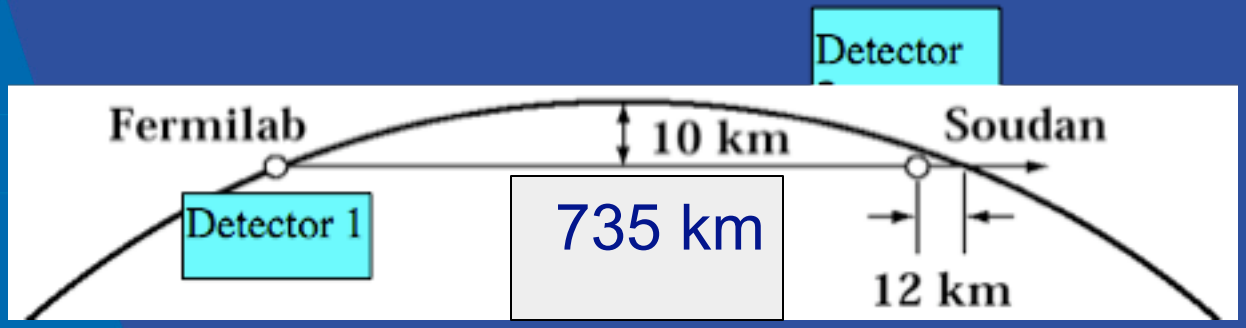


Moving from high energy to high intensity :

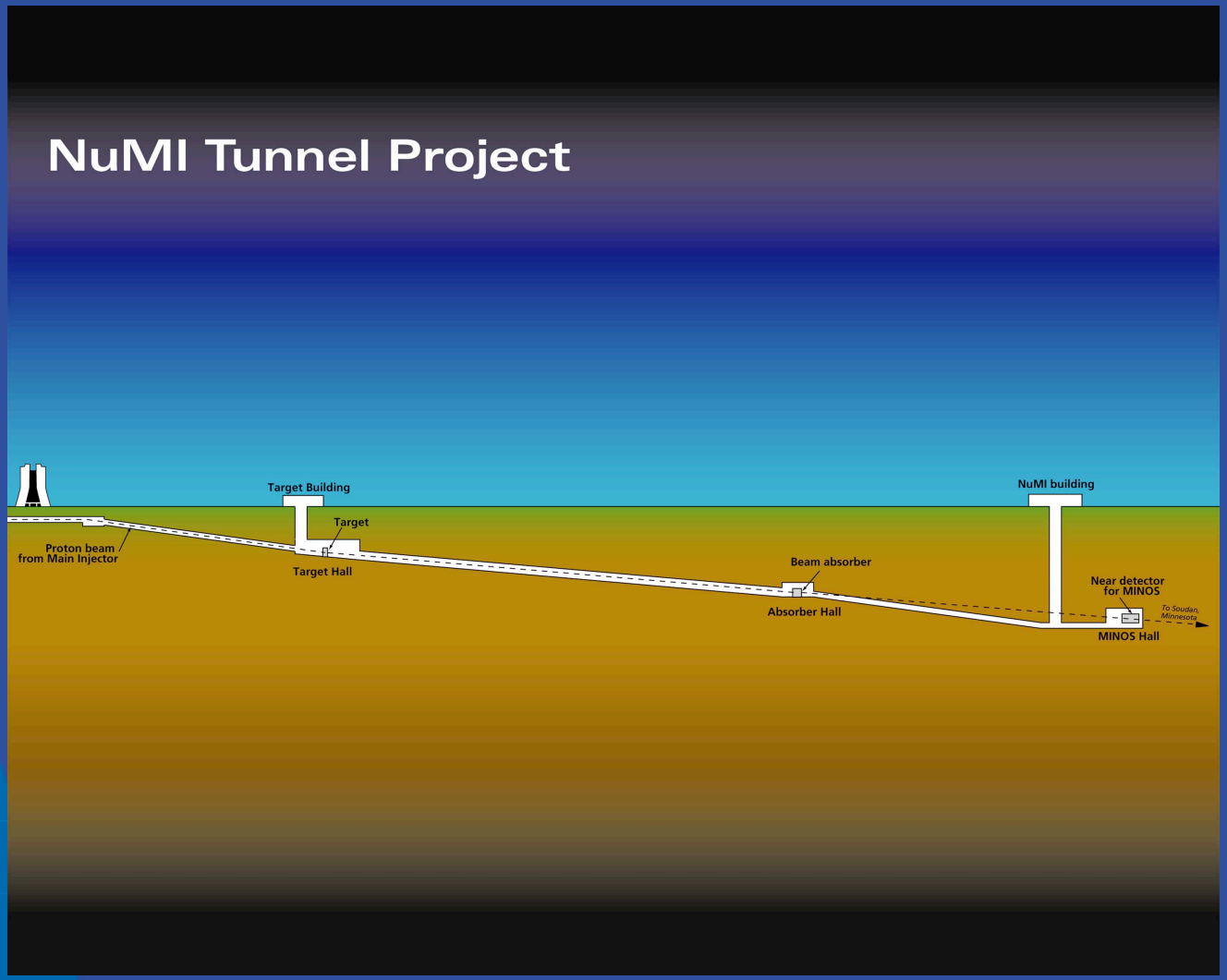
First steps to the Intensity Frontier

Main Injector Neutrino Oscillation Search : MINOS

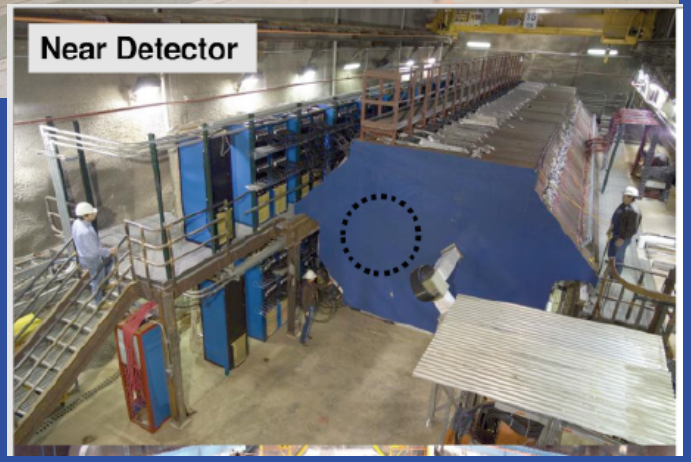




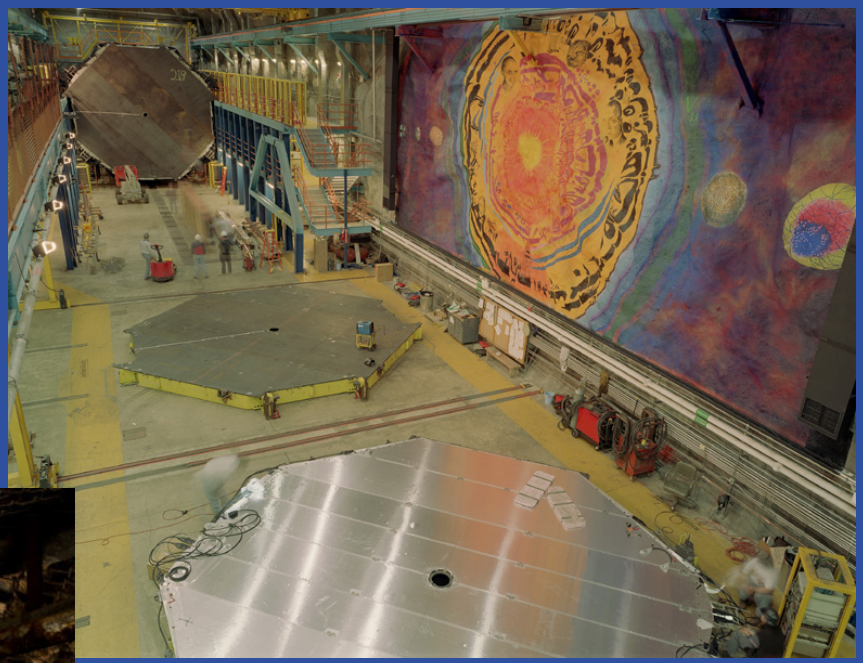
NuMI Tunnel Project

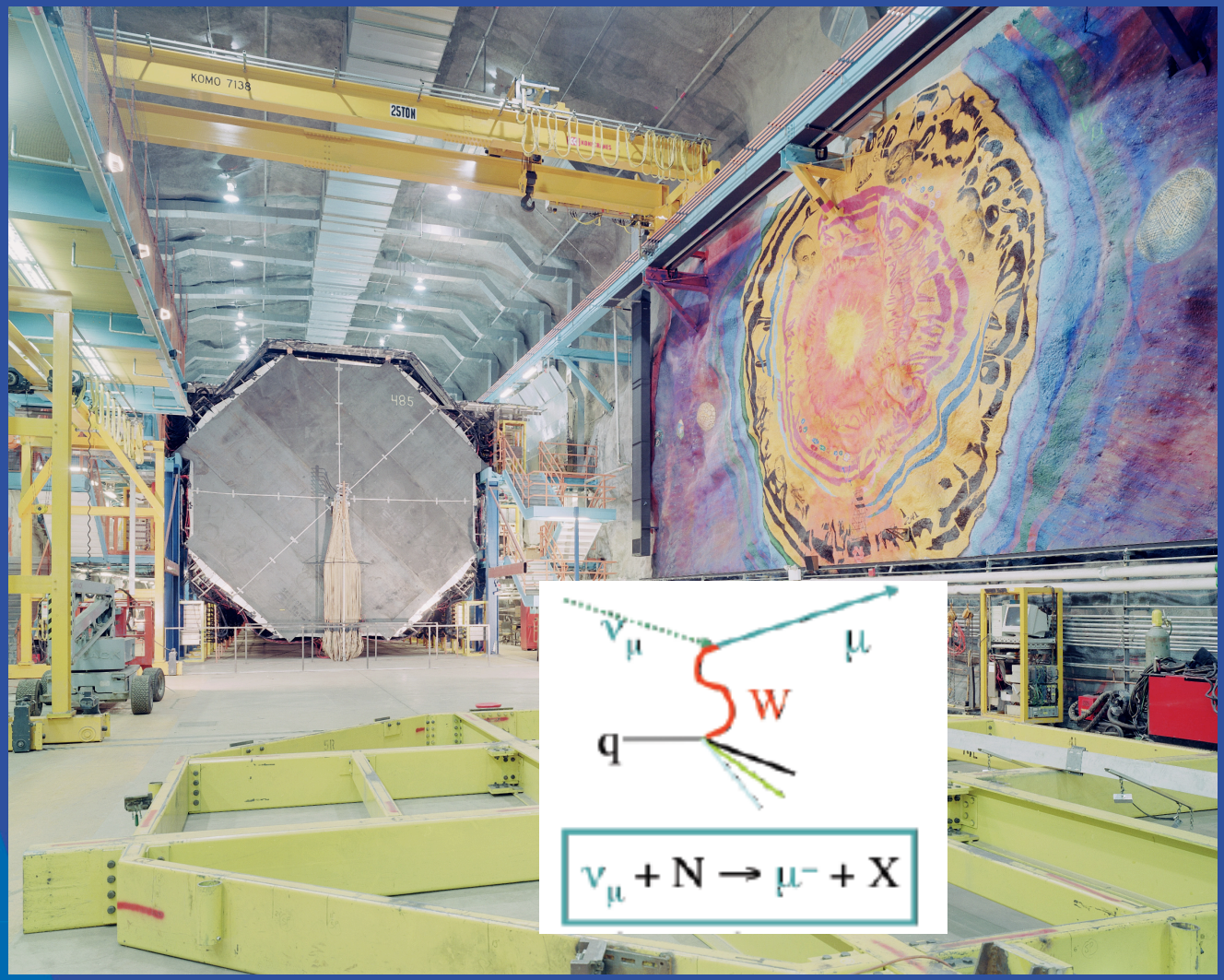


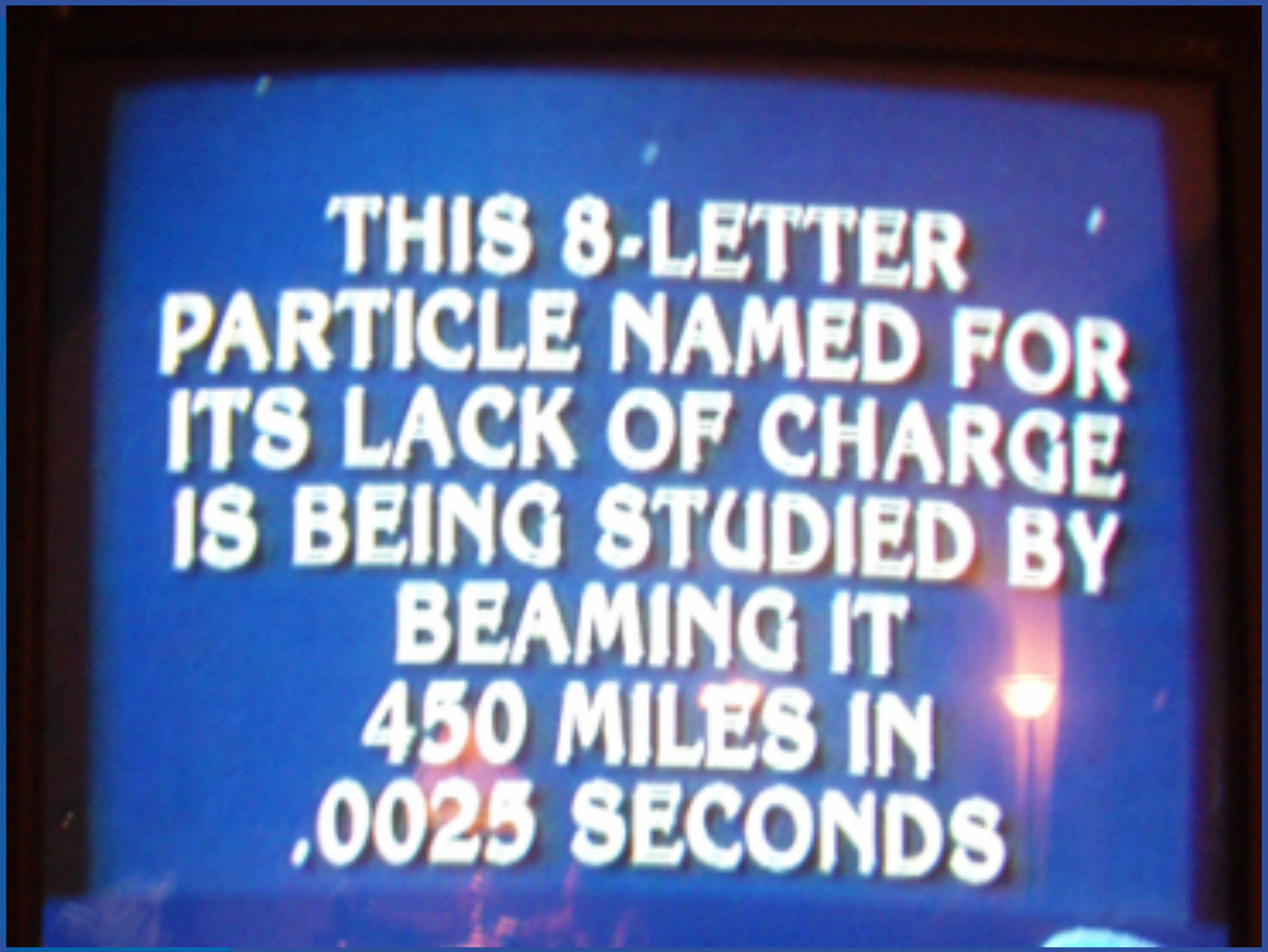
MINOS Near Detector



Building a ship in a bottle




KOMO 7138
25TON
485
ν_μ
μ
W
q
$\nu_\mu + N \rightarrow \mu^- + X$


THIS 8-LETTER
PARTICLE NAMED FOR
ITS LACK OF CHARGE
IS BEING STUDIED BY
BEAMING IT
450 MILES IN
.0025 SECONDS

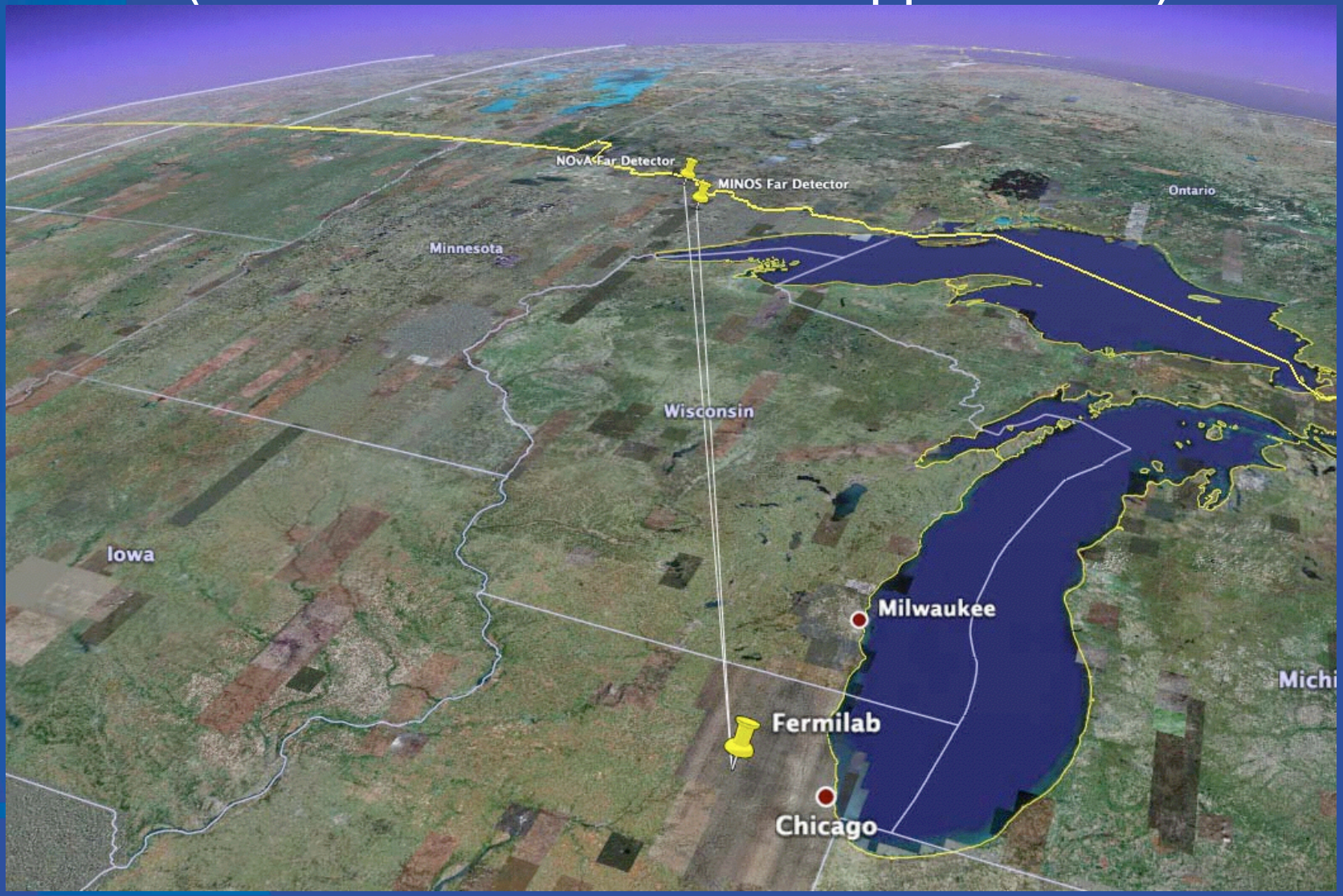
Some interesting numbers

- Proton beam delivers 4×10^{13} protons every 2sec
  - $\sim 10^{18}$ protons/day
  - Produce a few pions/proton
  - About half of the pions produce neutrinos aimed in the right direction
- Neutrino *flux* is $\sim 10^{13}$ /cm^2/sec
- Neutrino cross section is $\sim 10^{-38}$/cm^2/GeV
  - Few neutrinos each spill in Near Detector
  - Thousands per day in Near Detector
  - Predict a handful per day in Far Detector
  - Observe 60% of the predicted rate

How can we understand the neutrino better ?

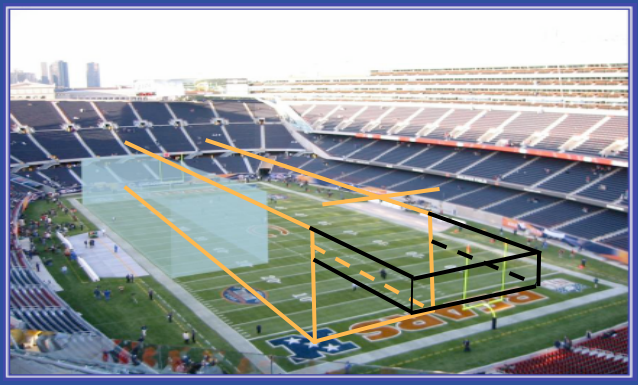
Next steps – we need to send the neutrinos over a further distance and look for muon neutrinos changing into electron neutrinos

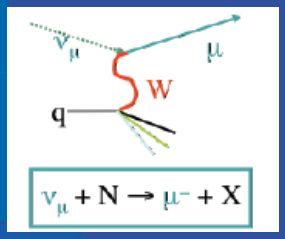
NuMI to NOvA
(NuMI Off-axis Neutrino Appearance)

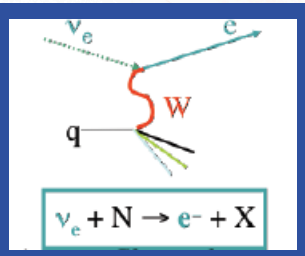


The NOvA Detectors

NOvA 14 kt & deep pit of building in "a" football stadium







NOvA groundbreaking - May 1, 2009

April 2010

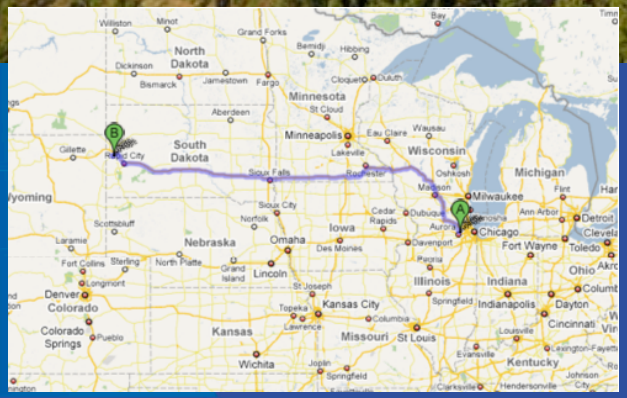
Construction complete : 2012

Data 2013 - 2019

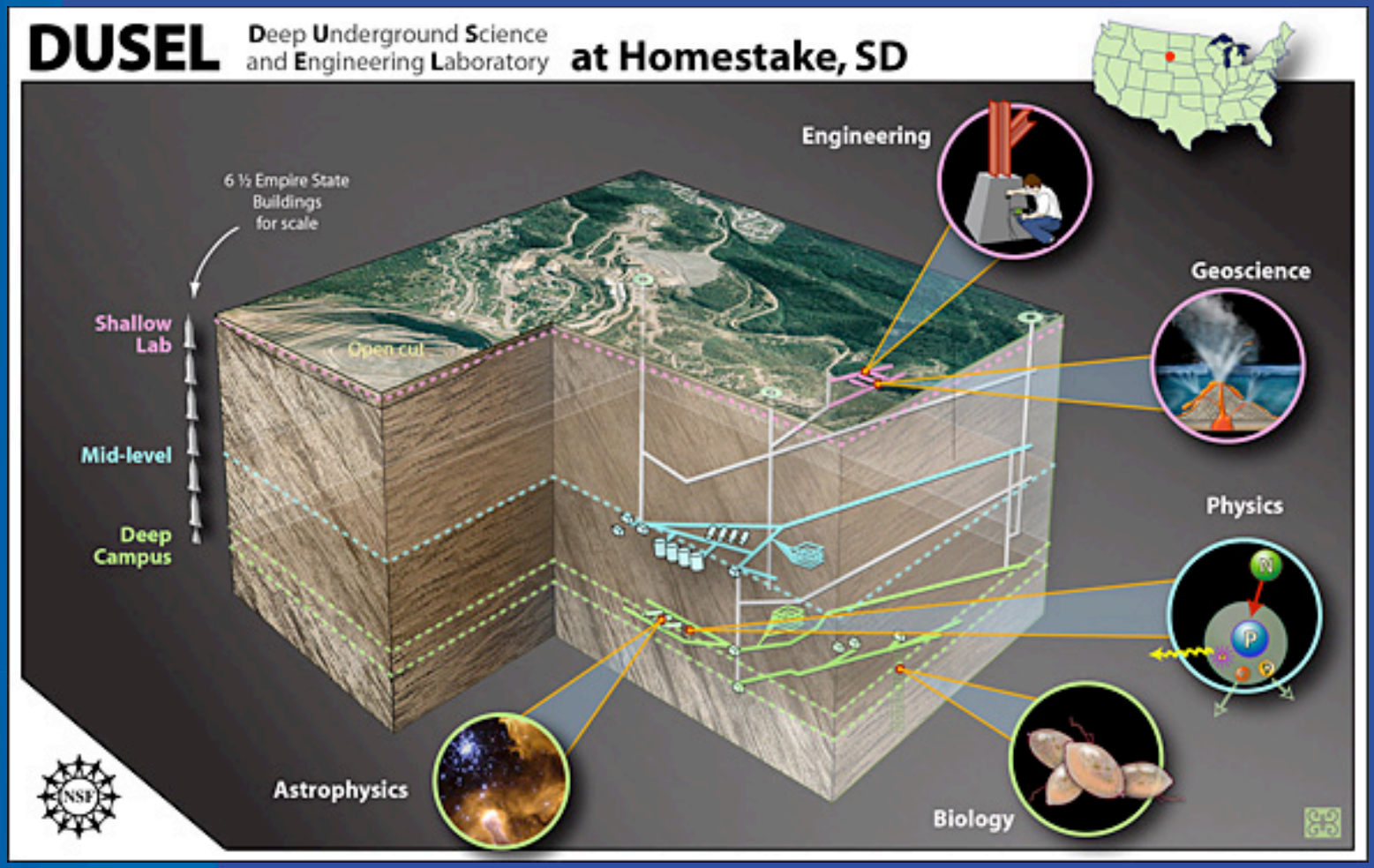
Beyond NoVA

A golden opportunity…..

Returning to the scene of the “crime”

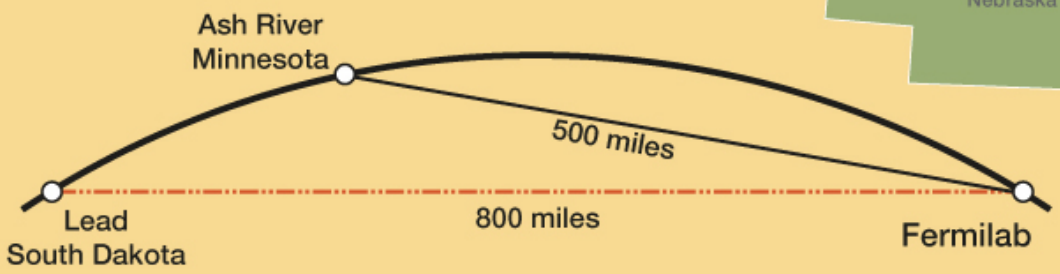


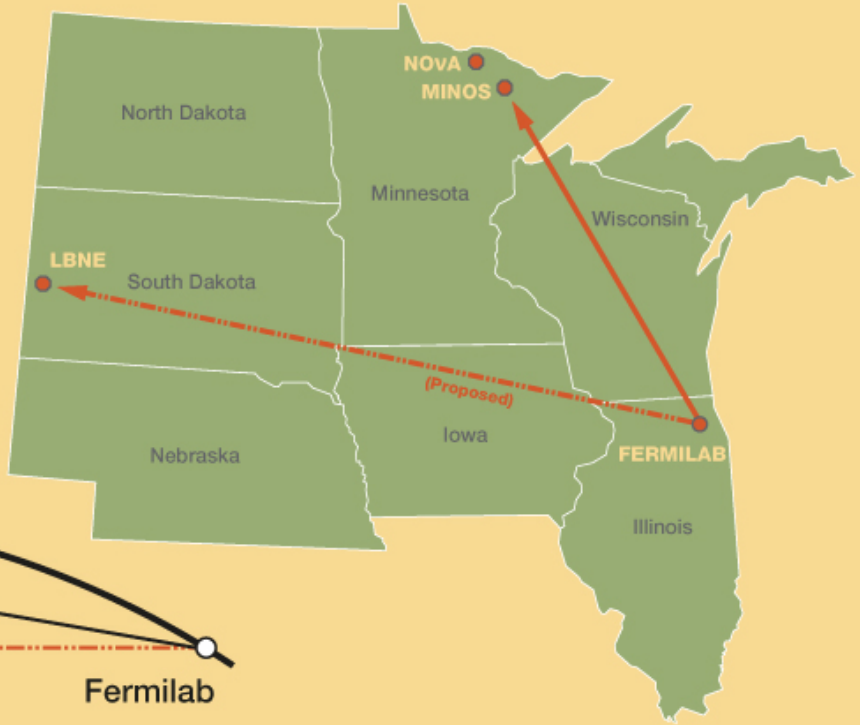
A Deep Underground Science and Engineering Laboratory in the United States



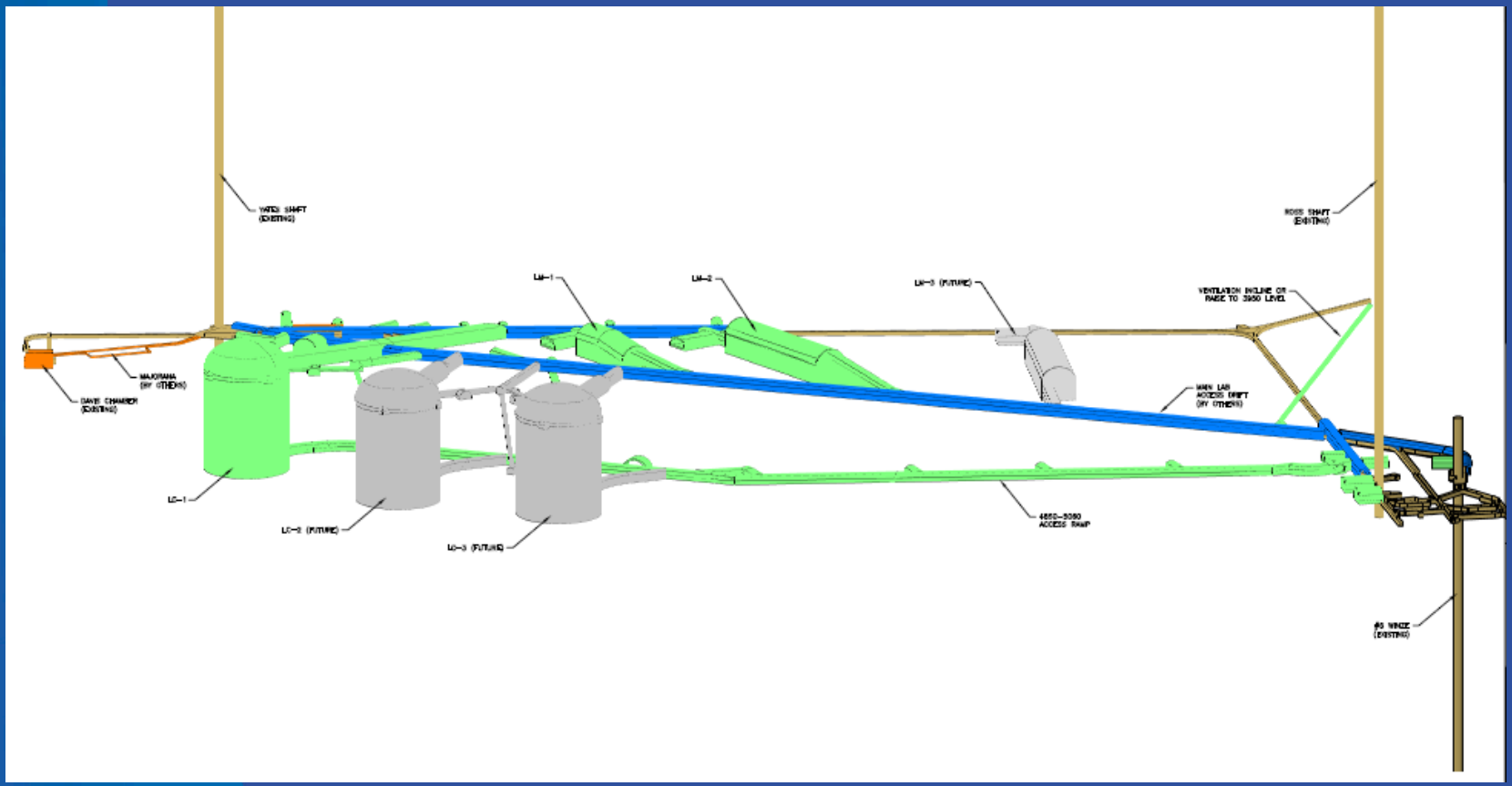
Straight Through the Earth

MINOS	Soudan Mine, MN	2340 ft deep
NOvA	Ash River, MN	Surface level
LBNE	Homestake Mine, SD	4850 ft deep

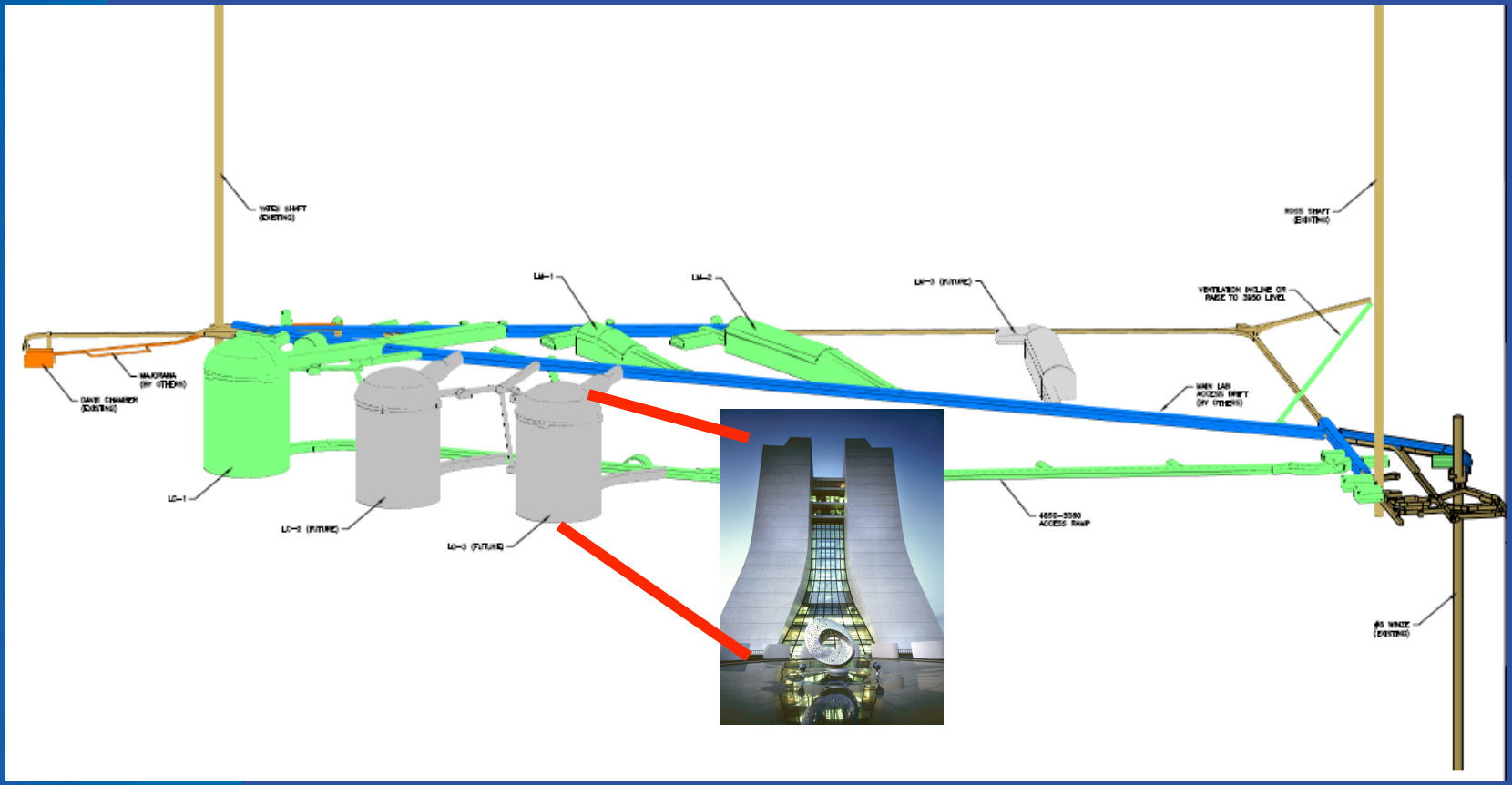




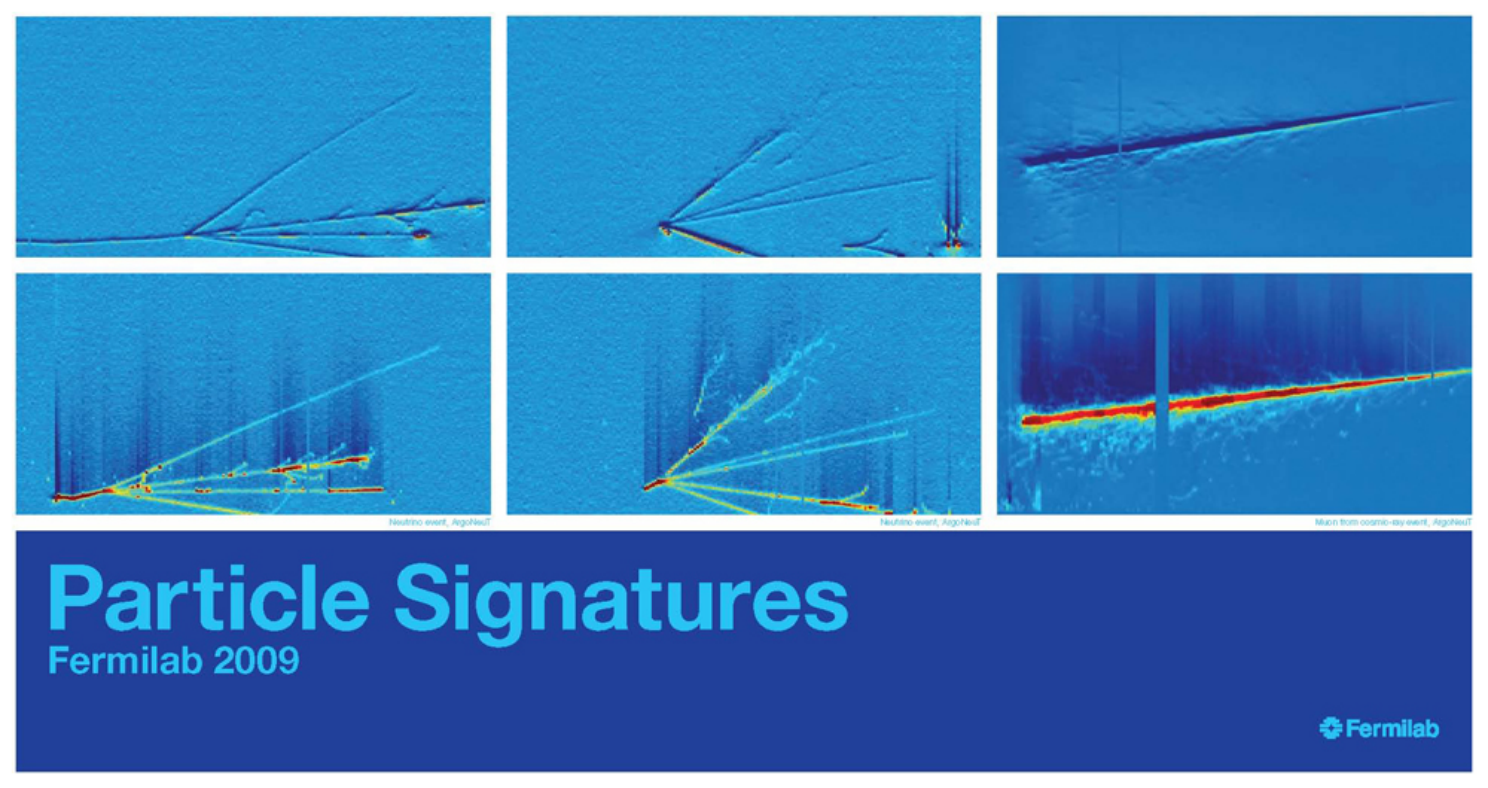
A complex of large detectors a mile below the earth's surface



A complex of large detectors a mile below the earth's surface

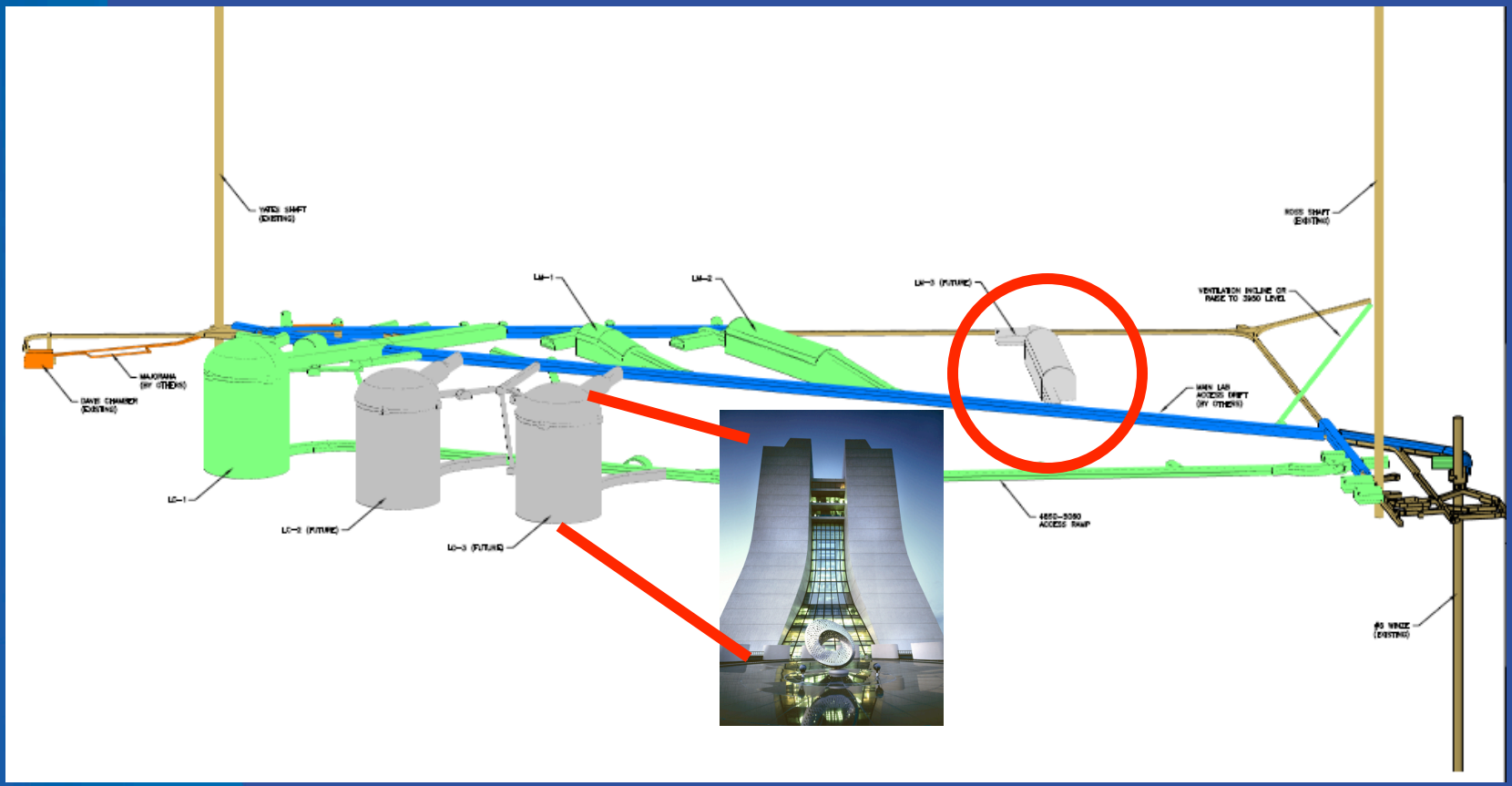


A new technology for detecting neutrinos : Liquid argon (87^0K = -303^0 F)



Images from a small prototype chamber in the NuMI beam

A complex of large detectors a mile below the earth's surface



Cosmic Gall revisited

Dear John:
A Poem by Joan Irwin

Neutrinos may be very small,
And do not interact at all,
We think. But do we really know?
Perhaps they do much more than flow.
You say they think the world is silly,
And pass right through it, willy-nilly.
You say they judge, ignore, and snub.
Insult us all! Ah, there's the rub!
(We do not like to be ignored.
It's even worse than being bored!)
They pierce and infiltrate. How sexy!
Despite their gall, they seem quite "flexie".
Perhaps they really are quite FAB!
We'll find out in our deep, deep lab!

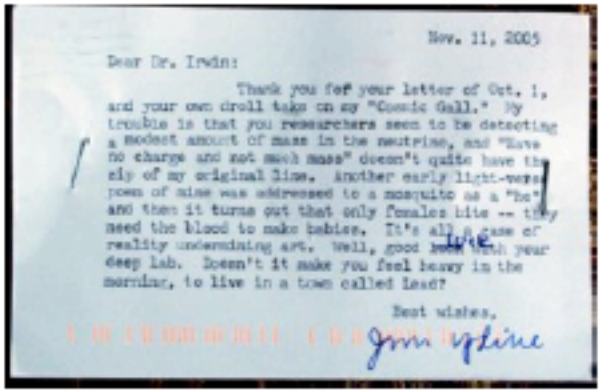
Dr. Joan Irwin holds a postcard from John Updike.

Updike responds:

Dear Dr. Irwin:

Thank you for your letter of Oct. 1, and your own droll take on my "Cosmic Gall." My trouble is that you researchers seem to be detecting a modest amount of mass in the neutrino, and "Have no charge and not much mass" doesn't quite have the zip of my original line. Another early light-verse poem of mine was addressed to a mosquito as a "he" and then it turns out that only females bite – they need the blood to make babies. It's all a case of reality undermining art. Well, good luck with your deep lab. Doesn't it make you feel heavy in the morning, to live in a town called Lead?

Best wishes,
John Updike



Nov. 11, 2005

Dear Dr. Irwin:

Thank you for your letter of Oct. 1, and your own droll take on my "Cosmic Gall." My trouble is that you researchers seem to be detecting a modest amount of mass in the neutrino, and "Have no charge and not much mass" doesn't quite have the zip of my original line. Another early light-verse poem of mine was addressed to a mosquito as a "he" and then it turns out that only females bite -- they need the blood to make babies. It's all a case of reality undermining art. Well, good luck with your deep lab. Doesn't it make you feel heavy in the morning, to live in a town called Lead?

Best wishes,

John Updike

John Updike's note to Dr. Joan Irwin

Dr. Irwin replies with another poem:

Oh heavy my heart (But not full of lead)
To hear you pronounce my town's name as "Led".
So correct you I must and my heart will not bleed,
If you will correct it – It's really called "Leed".

(A gold-mining term indicating a lead into a gold-bearing vein of ore)

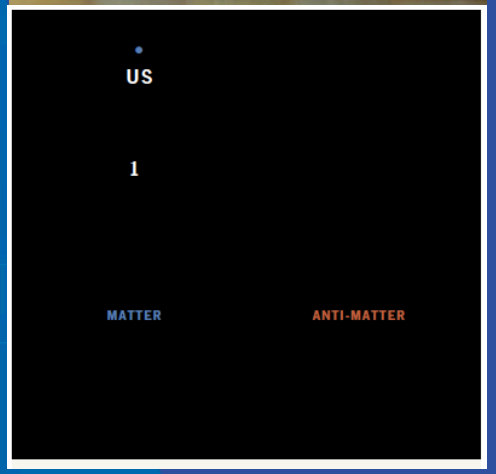
Thanks for responding. Keep watching the Times for news of our lab.

Sincerely,
Joan Irwin

John Updike, 1932-2009

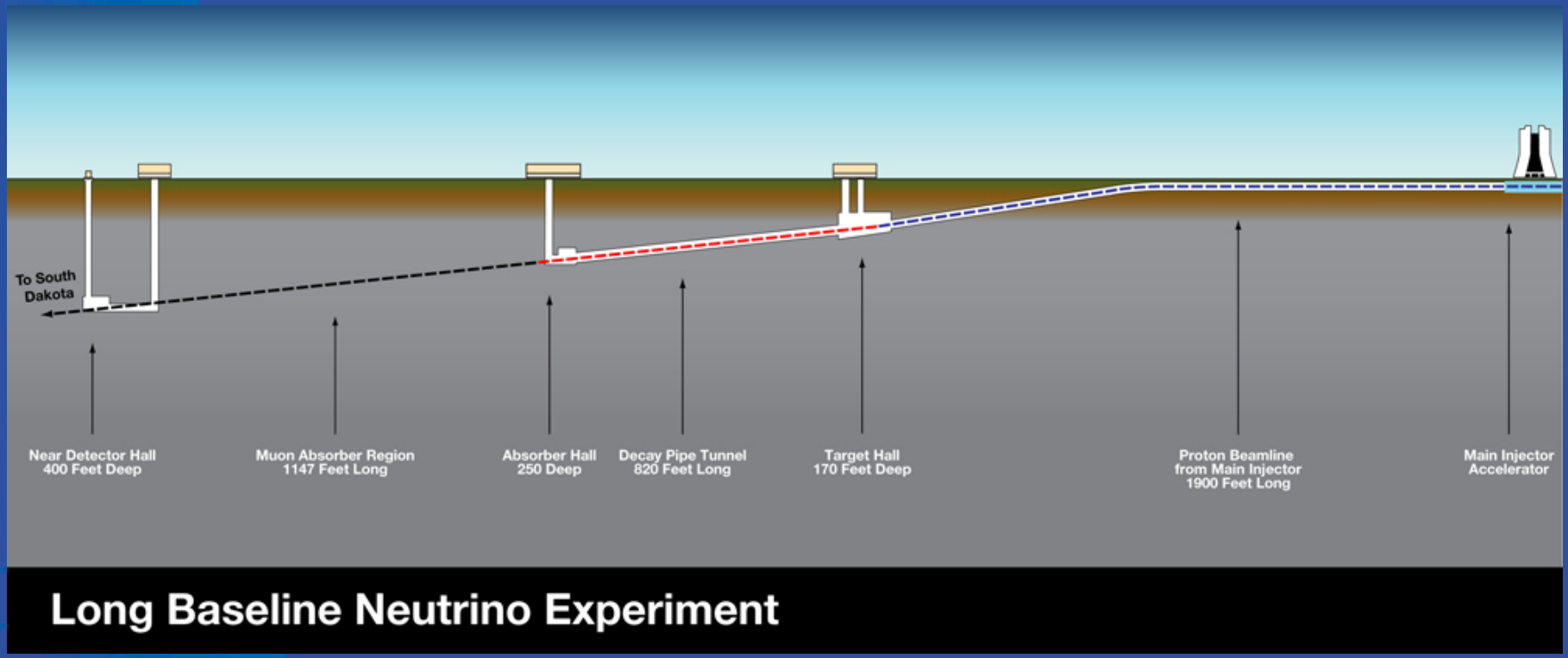
What do we want to learn from these experiments?

Long Baseline Neutrino Experiment (LBNE)

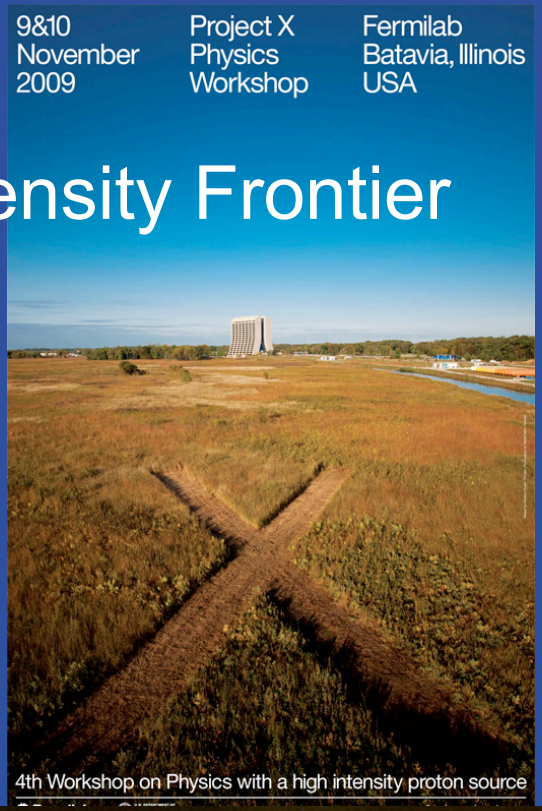


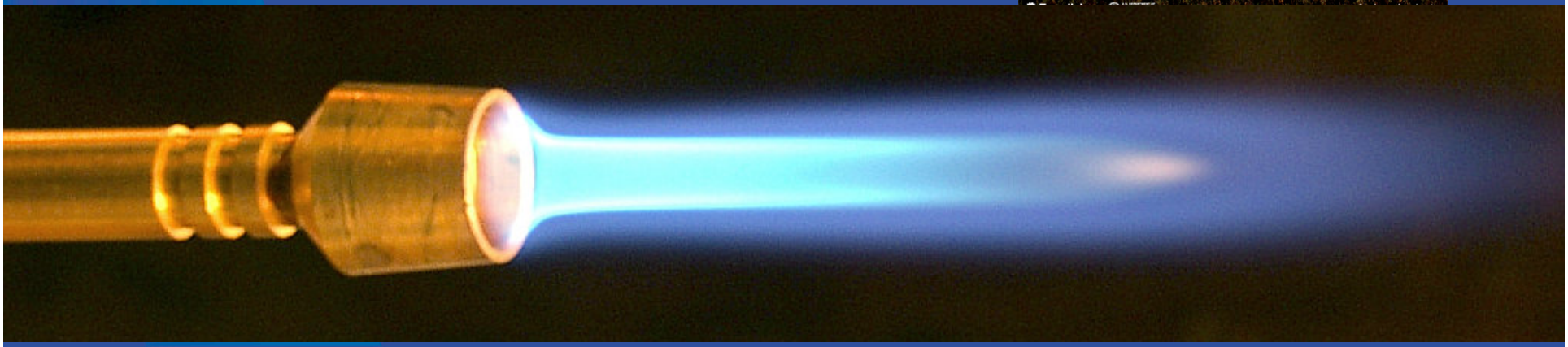
- Observe and quantify the rate at which muon neutrinos turn into electron neutrinos
- Measure properties of the neutrino masses
- Search for an asymmetry in the behavior of neutrinos and anti-neutrinos
  - Neutrinos are matter and a neutrino-anti-neutrino asymmetry may provide important clues to understanding the overall asymmetry of matter versus anti-matter in our universe

A new neutrino beam at Fermilab


To South Dakota
Near Detector Hall
400 Feet Deep
Muon Absorber Region
1147 Feet Long
Absorber Hall
250 Deep
Decay Pipe Tunnel
820 Feet Long
Target Hall
170 Feet Deep
Proton Beamline
from Main Injector
1900 Feet Long
Main Injector
Accelerator
Long Baseline Neutrino Experiment

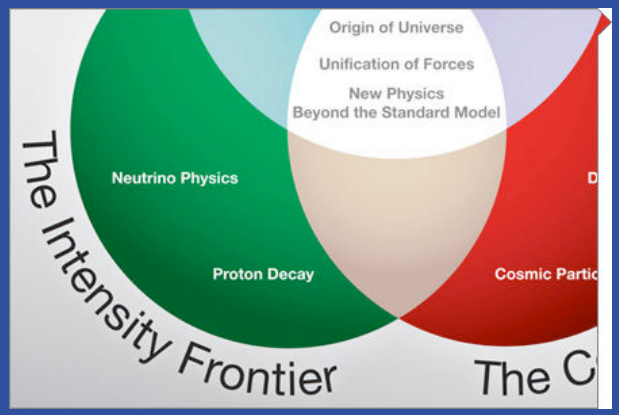
Extreme Beams at the Intensity Frontier





Status and Prospects of the LBNE and DUSEL Projects

- 2010 – 2013 : Project Design and Review
- 2014 – 2015 : Construction start if projects are approved and funded
- 2015 – 2020 : Construction
- 2020 – 20!! : Science at the Intensity Frontier



Thanks for your attention!

Thanks to many colleagues for pictures, material and ideas for putting this talk together.